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Statistical Analysis of Geomorphic, Petrographic and Structural Characteristics of the Dartmoor Tors, Southwest England

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May 1993

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The granite tors on Dartmoor are characterized and described by a combination of 21 geomorphic, petrographic and structural variables using two statistical approaches: analysis of significant correlations and multivariate analyses. Whereas an analysis of correlations enables relations between pairs of individual variables to be determined, the multivariate procedures addresses all variables at the same time. Spearman's rank correlation coefficient was used to correlate the variables so that nominal and ordinal variables could be included. The characteristics of summit tors and spur tors were defined by analyzing the significant correlations as well as by analyzing indirect relations between related variables. The multivariate procedures separated the sample of 58 tors into five clusters. Principal coordinates analysis and a non-hierarchical classification were used to determine the characteristics of each cluster. The joint spacing frequency distributions for the clusters were compared to determine statistically significant differences between them; each group is significantly different from at least two others. Comparing the results of the two procedures indicates that although all variable types are important to landform development, the geologic factors are most important. The most important variable types are rock texture, grain size, composition and structure.

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PREFACE

This report was prepared under DA Project 4A161102B52C, Task FO, Work Unit 201, "Image Analysis Research," in the autumn of 1992, under the supervision of Dr. J.N. Rinker, Senior Research Scientist, and of Mr. John V.E. Hansen, Director, Research Institute.

I wish to thank Dr. J.R. Hawkes, British Geological Survey, for providing the percent megacryst data; Dr. John Gerrard, University of Birmingham, England, who has reviewed this paper, for his useful advice and support; and Dr. Ann Benn and Mr. Kevin Slocum, TEC, both of whom gave me helpful reviews. Dr. Margaret Oliver, University of Birmingham, and Dr. Richard Morgan, University of Otago, New Zealand, also deserve thanks for their help in interpreting the multivariate procedures. Mrs. Jean Dowling, University of Birmingham, drew Figures 8, 9 and 10.

Mr. Walter E. Boge was Director, and COL Kenneth C. Kessler was Commander and Deputy Director of the U.S. Army Topographic Engineering Center at the time of publication of this report.

STATISTICAL ANALYSIS OF GEOMORPHIC, STRUCTURAL AND PETROGRAPHIC CHARACTERISTICS OF THE DARTMOOR TORS, SOUTHWEST ENGLAND

INTRODUCTION

This study is part of an effort to characterize the granite landforms of Dartmoor, southwest England, by statistically defining relationships between selected geomorphic, petrographic and structural variables.[1] The approach used is different from that of previous studies of granite landforms in two ways: (1) geologic characteristics were used in combination with geomorphic characteristics, and (2) typically descriptive characteristics were evaluated quantitatively in conjunction with numeric characteristics using statistical procedures. The purpose is to group, or classify, the Dartmoor tors by landform type using both geologic and geomorphic factors, and to determine which factors are most important with respect to the development of granite landforms.

The Dartmoor granite in southwest England (see figure 1) was chosen for study because of its classic, well-documented suite of landforms. Study of the Dartmoor tors has provided the basis for study of granite landforms worldwide. Tor is a Cornish word meaning tower and is used both locally in southwest England and worldwide to designate a certain type of granite landform. Linton (1955, p.476) defined tor genetically as:

> ...a residual mass of bedrock produced below the surface level by a phase of profound rock rotting effected by groundwater and guided by joint systems, followed by a phase of mechanical stripping of the incoherent products of chemical action.

Two statistical approaches are described: analysis of significant correlations and multivariate analyses. The analysis of correlations illuminated the relations between individual variables, such that a better understanding of the landform types was be obtained. Problems arise in this type of analysis, however, because multiple interrelationships are not defined -- the effects of third or fourth variables on a given significant correlation are unknown, although they can sometimes be estimated. Because there are so many factors involved in a study such as this, multivariate statistical analyses are an appropriate method of investigation. All factors can be evaluated at the same time, multiple interrelationships can be identified, and the relative importance of each factor type can be determined.

Other statistical approaches to characterizing the Dartmoor tors using the same variables have been discussed previously (Ehlen, 1991, and Ehlen, 1992). Ehlen (1991) evaluates joint spacing frequency distributions with respect to joint type, relative relief, landform, grain size and rock texture. Joint spacing distributions are significantly different for each type of tor evaluated: joint spacing becomes wider in the order pinnacle, valleyside tor, spur tor, summit tor. These relations place restrictions on landform evolution. Ehlen (1992) addresses the distributions of the variables across Dartmoor, i.e. spatial patterns. Variable maps prepared using a GIS were compared, enabling valleyside, spur and summit tors to be characterized semi-quantitatively with respect to relative relief, rock texture, composition, grain size and joint spacing.

[1] see Ehlen (1991) and Ehlen (1992)

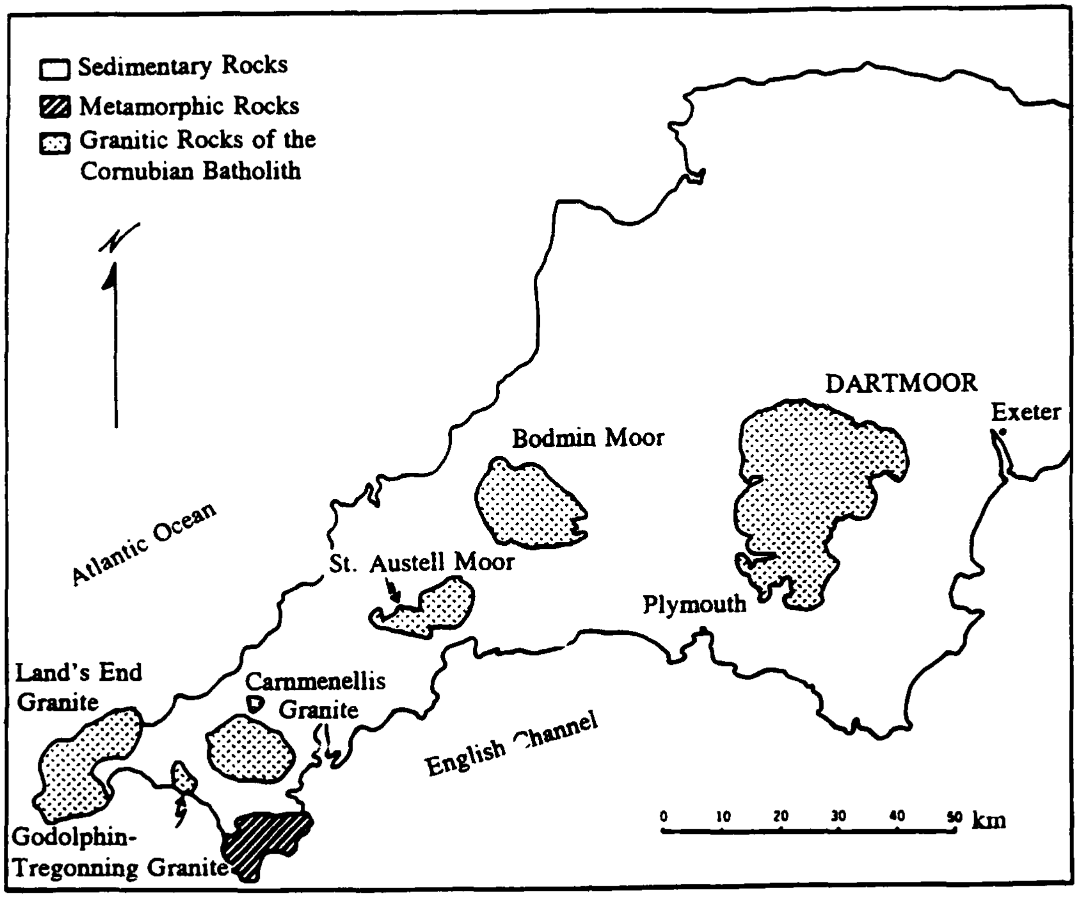


Figure 1. Location of Dartmoor and the Cornubian Batholith.

Geology of Dartmoor

Dartmoor is the most significant highland in southern Britain, forming a plateau that dips gently to the southeast. Elevations range from 150 to 600 meters. The rock outcrops, or tors, are usually isolated and occur on hill and ridge crests, on spurs, and along the sides of valleys, usually on the upper slopes. Few occur in valleys. Tors are also common above the escarpment along the edges of the granite. Figure 2 is typical of the landscape. The tors, which range in size from small outcrops to large, massive monoliths, are located on buried domes. Although there are many theories for the origin of tors, on Dartmoor they most likely result from deep, subsurface, chemical weathering in a climate slightly warmer than that of today, followed by periglacial removal of the weathered debris (Linton, 1955).

The Dartmoor granite, which covers approximately 625 square kilometers, forms the easternmost exposure of the Cornubian batholith (Figure 1). The rocks are megacrystic, peraluminous, biotite granites. The most common minerals are quartz, potassium feldspar (mainly orthoclase) and plagioclase feldspar (mainly albite, but some oligoclase). Other important minerals are biotite, tourmaline and garnet. Tourmaline occurs in both primary and secondary phases. Common accessory minerals include zircon, apatite, muscovite, ilmenite and cassiterite (Brammall, 1926). The granite was emplaced probably as a crystal mush during the Variscan orogeny in the late Carboniferous or early Permian (Exley and Stone, 1964); the rocks are thus about 285 to 295 million years old (Darbyshire and Shepherd, 1985). Textural evidence suggests emplacement was rapid (Hawkes and Dangerfield, 1978). The Dartmoor pluton was injected from the south, and is deeper and thicker along the southern margin, thinning steadily northward (Bott et al., 1958; Dearman, 1964).

Figure 2. Typical Dartmoor Landscape (Bonehill Rocks).

Although the granite was emplaced at a relatively high level in the crust, comparatively little erosion seems to have occurred. The earliest occurrence of high proportions of Dartmoor detritus is in Late Cretaceous sedimentary rock, indicating that the main body of the intrusion was exposed at that time (Groves, 1931). The present level of exposure is near the top of the original pluton (Reid et al., 1912; Dangerfield and Hawkes, 1963) and the roof is exposed in several places. Extensive alteration, including potassium metasomatism, tourmalinization, kaolinization and greisenization (Exley and Stone, 1964), has occurred since emplacement. Most alteration is hydrothermal in origin and probably occurred early in the history of the pluton. Some alteration processes, such as kaolinization, are thought to be ongoing (Durrance et al., 1982). Kaolinization and greisenization of the granite have made it susceptible to weathering, so excellent exposures of growan/saprolite occur. Other parts of the pluton, however, have become more resistant as a result of alteration. Mineralization, which was later, is associated with emplacement of mafic dikes.

Background

There is a general consensus among those who have studied granite landforms that geologic factors exert significant control on their shapes and locations. Joints, for instance, are often cited as controlling landform shape (e.g. Waters, 1957; Thomas, 1974; and Pye et al., 1984). Certain types of landforms are defined in terms of joint spacing, e.g. domes develop only where joints are very widely spaced (e.g. Mabbutt, 1952; Twidale, 1964, 1982; Cunningham, 1971). Composition, grain size and rock texture have also been shown to play important roles. Brook (1978) and Robb (1979), among others, found that where potassium is enriched in granites, usually in large and abundant megacrysts, larger and more prominent landforms are produced. Furthermore, inselbergs tend to occur where potassium feldspar contents are high: rocks in areas without inselbergs tend to be low in potassium feldspar (Dumanowski, 1964, 1968; Pye et al., 1986). With respect to composition, Ehlen and Zen (1986) report that vertical joints are more closely spaced in mafic igneous rock than in acidic rock. In addition, outcrops of more mafic rocks, such as quartz diorite, tend to be smaller than those formed of rocks such as granite. Demek (1964) and Ollier (1978) found that landform boundaries often coincide with lithologic or petrographic boundaries. Bateman (1965), Gilbert (1982), and Ehlen and Zen (1986) determined that joint spacing is narrower where the rocks are finer grained. Rock texture is also important. Gibbons (1981) and Pye et al. (1984) found megacrystic rocks are more resistant to weathering and erosion than nonmegacrystic rocks. There has, however, been no attempt to identify or define these relations on a broad scale or to pinpoint the precise roles of the various factors involved. Consequently, there is almost no quantitative data supporting this consensus, and only Robb (1979) and Gerrard (1974, 1978) have applied statistical procedures to define better these relations.

Robb's (1979) work involved the study of rates of weathering in different South African granites. Because evidence relating to grain size and rock texture was contradictory, he concluded that, although important, neither variable was decisive with respect to weathering rates. He investigated element mobilities and the stability of mineral phases using trend surface analysis and determined that stability is more important than mobility with respect to weathering rates. The results of this analysis were used to identify the mode and sequence of crystallization of the granite.
By comparing joint and stream course distributions on Dartmoor, Gerrard (1974) determined that the drainage net is controlled by major regional fractures, and that weathering along these joints was responsible for formation of the initial compartments or domes. Tors developed on the domes as a result of "secondary" jointing, caused by stress release within compartments, which resulted from further, more localized weathering and stream incision. He also compared the distributions of relative relief for summits with and without tors, and found that tors typically occur on summits with more than 100 meters of relief within a horizontal distance of 800 meters. Using these relationships, among others, Gerrard grouped the tors as (1) summit tors, (2) valleyside and spur tors, and (3) emergent tors.

In a later paper, Gerrard (1978) compared joint spacings, slope angles and tor heights for 65 tors on Dartmoor and Bodmin Moor (see Figure 1). This resulted in regrouping the tors as (1) summit and valleyside tors and (2) emergent tors. Gerrard found vertical joint intensity to be greater and more variable in the summit and valleyside tors than in emergent tors; these differences are statistically significant. Tor height was significantly less for emergent tors as well, but there were no significant differences in height between summit and valleyside tors. The same relationships hold with reference to slope: slopes surrounding emergent tors are typically more gentle than slopes surrounding summit and valleyside tors. He concluded that summit and valleyside tors occur where joints are closely spaced compared to the rest of the dome, but not so closely spaced that everything is weathered and removed, and that emergent tors are probably the result of chance exposure.

Definitions and Procedures

The variables evaluated in this study were chosen in part because of the previous work described above and in part because field observations of granite landforms in parts of the United States (e.g. Montana, California, Wyoming, Missouri, Arizona, Georgia) suggested intriguing variable interrelationships (e.g. coarse grain is often associated with widely spaced orthogonal joints, the weathered product of the combination being very large boulders). The variables comprise three groups: geomorphic variables, structural variables, and petrographic variables.

Geomorphic Variables

Relative relief was determined from U.K. Ordnance Survey 1:25,000-scale topographic maps and was defined using Gerrard's definition, i.e. the vertical distance between the tor and the nearest main stream within a horizontal distance of 800 meters. As discussed above, Gerrard (1974) suggested that, because most tors occur on summits and ridges with relative relief > 100 meters, relative relief is important to the distribution of tors on Dartmoor.

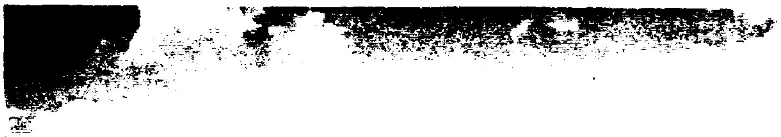
Landforms were classified according to topographic position as summit tors, spur tors, and valleyside tors using the 1:25,000-scale topographic maps. This classification is similar to that used by Gerrard (1974, 1978) and noted by Linton (1955). Summit tors occur on hill crests or ridges, usually at the highest point, and as small domes (Figure 3). Except in the latter case, slope away from the tor is gentle. Spur tors occur at the ends of ridges or spurs, above the break in slope defining the valley side (Figure 4). Slope away from spur tors is also gentle. Valleyside tors occur below the break in slope defining the valley side and slopes both above and below are steep (Figure 5). Tor height is greater on the downslope side. These categories were chosen because it was thought that stresses caused by valley incision would produce different joint patterns in tors in these positions.

Joint control, determined by observation in the field, is a subjective evaluation of which type of joint appears to be most important to the shape of the tor. Tor shape on Dartmoor is usually controlled by one of three joint sets -- a horizontal set forming the upper surface, a vertical set perpendicular to the face of the tor forming its sides, or a second vertical set parallel to and forming the face of the tor. Joint sets may also control tor shape in combination. As an example, the shapes of castellated tors appear to be controlled by both horizontal and vertical joints (Figure 6A); whereas, the shapes of lamellar tors, those with very closely-spaced horizontal joints and sparse, very widely spaced vertical joints, appear to be controlled by horizontal joints (Figure 6B).

Structural Variables

Joint spacing is the distance between successive joints in a given joint set, measured normal to the planes of the joints along a linear traverse of continuous outcrop. A **joint set** is a collection of individual joints that are essentially parallel with similar inclination. **Vertical joints** are defined as dipping 70° or more, whereas **horizontal joints** dip 25° or less. Joints in the intermediate category are sparse on Dartmoor and were not addressed. Joints were also classified as primary or secondary (Figure 7). **Primary joints** are long, usually open joints that typically cut across other joint traces and appear to control the shapes of the tors. **Secondary joints** are shorter joints, local in extent, that usually do not cross other joint traces. No genetic connotation is implied by these terms.

Joint spacing was measured at 58 sites (Figure 8) between approximately 7000 joints in 185 joint sets in tors containing at least three joint sets. Only spacings between joints in sets that extended throughout the tor were measured. Such joint sets are more likely to affect tor shape than those that extend only part way through. Mean joint spacing for a sample site was determined by combining joint sets according to joint type. Ratios between horizontal and vertical joint spacings for both primary and secondary joints are also included. The joint spacing measurements are published in Ehlen and Zen (1990).



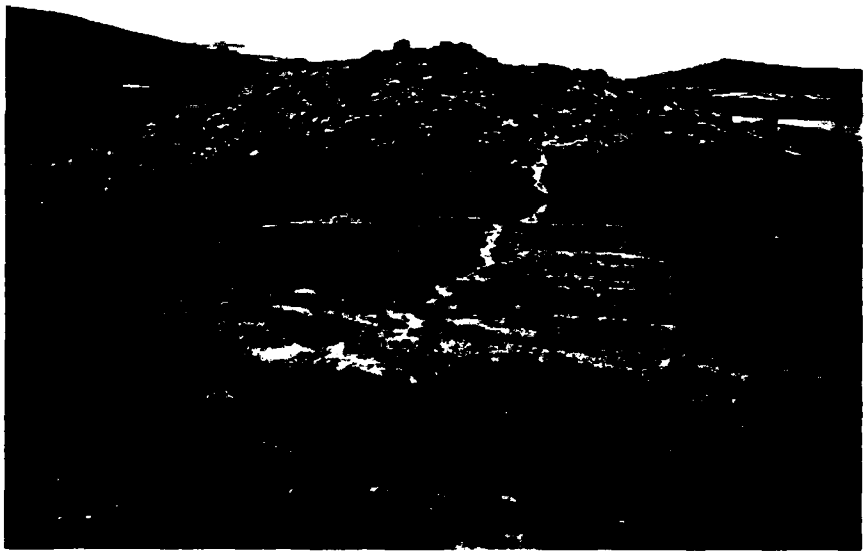


Figure 3. Summit Tor (Honeybag Tor).

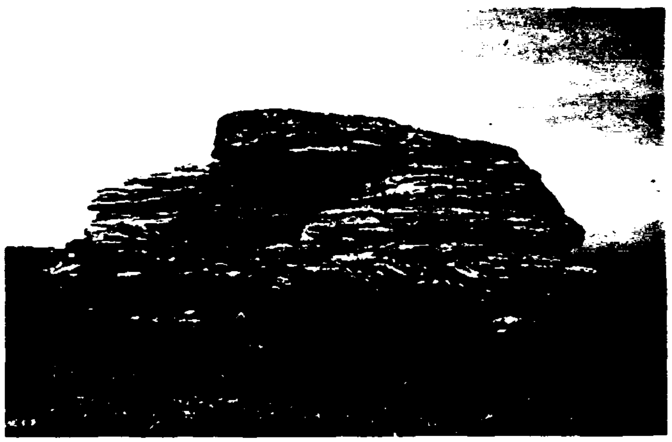
Petrographic Variables

Grain size was determined microscopically on stained, cut slabs. Cut slabs were used, rather than thin sections, because the granite is very coarse grained (see Ehlen and Zen (1986) and Ehlen (1989) for details of the procedure). Mean grain size was based on 750 grains per sample. Quartz, potassium feldspar and plagioclase feldspar grains were measured. Potassium feldspar grain size refers only to groundmass; the very large megacrysts were treated separately (see rock texture, page 10).

Figure 4. Spur Tor (Little Trowlesworthy Tor).

Figure 5. Valleyside Tor (Black Tor).

A. Combined Vertical and Horizontal Joint Control (Hound Tor)



B. Horizontal Joint Control (Branscombe's Loaf)

Figure 6. Joint Control of Outcrop Shape

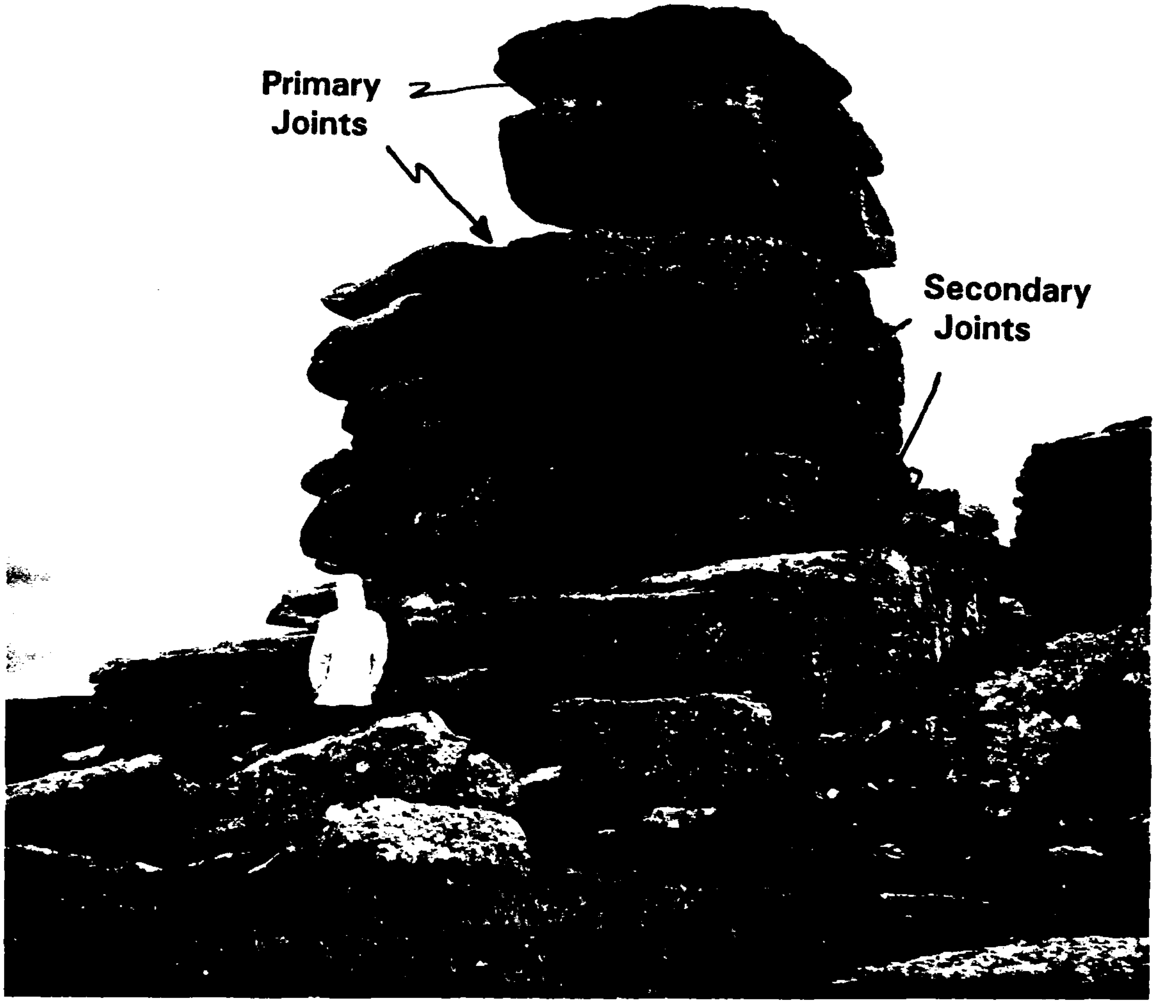


Figure 7. Primary and Secondary Joints.

Composition was also determined microscopically from the cut slabs as modal percents based on 750 grains per sample. Tourmaline is included in addition to quartz, potassium feldspar and plagioclase feldspar because of its high abundances and extreme hardness.

Tourmaline also occurs as joint fillings, usually in closely spaced secondary vertical joints, in zones that are more weathered than the surrounding rock. Presence or absence, which might provide insight into susceptibility to weathering, was determined in the field. Schorl, which results from the alteration process tourmalinization and which is common throughout the Cornubian batholith, consists of small, distinct, usually rounded blebs of quartz and tourmaline that are very hard and are distributed unevenly throughout the rocks. Presence or absence, which might affect joint spacing, was determined visually in the field as well as from cut slabs. Clay, probably kaolinite (E-an Zen, personal communication, 1988), resulted from either a late- or post-magmatic, low-temperature thermal event (i.e. 300-500°c) or from weathering, or a combination of the two (Bristow, 1977). It was identified in thin section.

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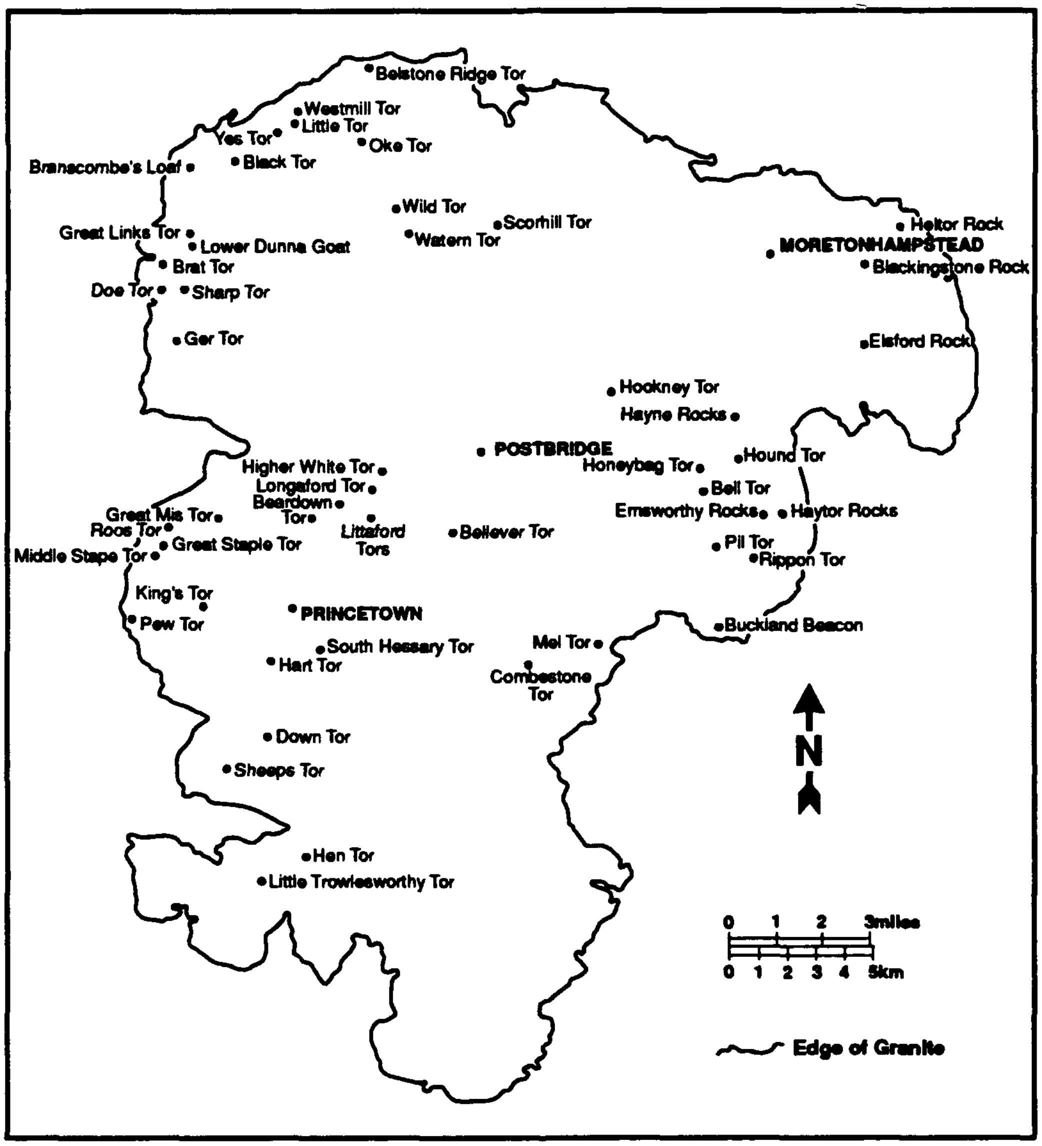

Figure 8. Location of Sample Sites.

Rock texture is addressed because of the possible effects of the large megacrysts (up to 18-20 centimeters in length) on joint spacing. Megacrysts were counted in the field using a standard botanist's quadrat (0.25 square meter). The number of megacrysts within the quadrat longer than 2.5 centimeters in an exposure typical of that outcrop was recorded. Although quartz and plagioclase feldspar megacrysts are present, only potassium feldspar megacrysts meet the length requirement. Percent potassium feldspar megacrysts, determined microscopically, addresses the same concerns as number of megacrysts, but on a volume basis. Grain size distribution, determined visually from the stained, cut slabs, was addressed as either equigranular or megacrystic and also refers only to the large potassium feldspar megacrysts.

ANALYSIS OF CORRELATIONS

Introduction

Analysis of statistical correlations comprised the initial evaluation of the relations among these variables. The nonparametric procedure, Spearman's rank correlation coefficient (ρ), was used, rather than Pearson's product moment correlation coefficient (r) for three reasons. First, it allowed inclusion of binary and nominal variables, and second, it accommodates data that is not normally distributed. Finally, ranks are not necessarily affected by closed or constant-sum data, e.g. percentages (Rock, 1988). Correlations calculated from closed data are much more negative than they should be (Davis, 1986; Rock, 1988). Although there is little that can be done about the problem, Rock (1988) states that using rank correlation coefficients may be better than product-moment coefficients: closure must effect r, but ρ is not necessarily affected.

The lower half of the correlation matrix forms Table 1. The coefficient defining a significant correlation is 0.262. Table 2 defines the abbreviations used in Table 1 and throughout the text. Finally, significant correlations between variables are shown graphically in Figure 9.

The following discussion refers only to significant correlations at the 95% confidence level unless otherwise noted. For the binary variables, coded 1 = presence and 2 = absence, a positive correlation is with a higher number. A positive correlation with schorl, tourmaline veins and clay indicates absence. The nominal variables are also coded. The three landform types, spur tors, valleyside tors and summit tors, are coded 1, 2, and 3, respectively. The grain size distributions, equigranular and megacrystic, are coded 1 and 2, respectively. Horizontal, vertical, or combined horizontal and vertical joint control are coded 1, 2, and 3, respectively. For example, if a given variable is highly, positively correlated with landform, the landform type involved would be summit tors, which are coded with the highest number. High positive correlations with these variables thus refer to summit tors, megacrystic rocks, and combined horizontal and vertical joint control of tor shape. Although valleyside tors are common on Dartmoor, the coding system precludes their characterization in the analysis of correlations. Two types of relations between variables are discussed: (1) significant correlations at the 95% confidence level and (2) indirect or "third-party" relations between variables not significantly correlated with each other, but both of which are significantly correlated with the same third variable. The latter will be referred to as indirect relations. Correlations that are not significant are also occasionally discussed, but the absence of a significant relation is also noted appropriately.

Discussion of Significant Correlations

Correlations with Geomorphic Variables

The geomorphic variables are relative relief (REL), landform (LF), and joint control of outcrop shape (JC). Of these, only relative relief and landform are significantly correlated (Table 1). Correlations between these two variables and joint control are positive, however, indicating that the shapes of summit tors with high relative relief are more likely to be controlled by vertical joints, or by vertical and horizontal joints combined, than by horizontal joints alone.

Table 1. Correlation Matrix

	Geomorphic Variables:			Structural Variables:				Petrographic Variables: Grain Size:				Composition:							Rock Texture:		
	REL	LF	JC	MVPS	MVSS	MHPS	MHSS	MRGS	MQUA	MKSP	MPLG	PQUA	PKSP	PPLG	PTM	SCHR	VEIN	CLAY	GSD	PHEN	MEGA
REL	1.000																				
LF	.363	1.000																			
JC	.068	.198	1.000																		
MVPS	.020	.270	-.169	1.000																	
MVSS	.142	.278	-.264	.622	1.000																
MHPS	-.012	.202	.184	.422	.055	1.000															
MHSS	-.058	.183	.333	-.021	-.002	.565	1.000														
MRGS	-.068	.101	.044	-.040	.120	.031	.233	1.000													
MQUA	-.024	.116	.050	.044	.168	.172	.263	.940	1.000												
MKSP	.112	.097	.074	-.096	.040	-.041	.186	.918	.842	1.000											
MPLG	.173	.140	-.073	.135	.262	.027	.141	.655	.559	.420	1.000										
PQUA	-.211	.102	.167	-.139	-.153	-.223	-.193	.355	-.471	-.216	-.440	1.000									
PKSP	-.201	.218	.003	-.047	-.190	-.179	-.181	.315	-.397	-.207	-.010	.528	1.000								
PPLG	-.009	.023	.143	-.141	-.024	-.004	.133	.107	.225	.043	-.018	-.575	-.603	1.000							
PTM	.326	.215	.028	.309	.219	.219	-.034	.246	.301	.211	.363	-.286	-.412	-.185	1.000						
SCHR	.284	.237	.352	.297	.172	.413	.390	.114	.162	.141	.124	.229	.121	.267	.212	1.000					
VEIN	.193	.387	-.062	.166	.248	.140	.234	.147	.184	.088	.230	.072	.050	.343	-.006	.116	1.000				
CLAY	.266	.199	.184	.258	.265	.163	-.016	.017	.017	.027	.144	-.018	.130	.057	.076	.357	.160	1.000			
GSD	.452	.503	.399	.429	.430	.305	.344	.366	.318	.330	.563	.363	.288	.152	.505	.529	.422	.408	1.000		
PHEN	.241	.308	.041	.295	.160	.134	.119	.092	.045	.104	.549	.300	.264	.033	.187	.218	.271	.161	.653	1.000	
MEGA	.267	.417	.091	.249	.111	.086	.164	.161	.141	.118	.354	-.101	-.116	-.112	.201	.212	.637	.186	.637	.805	1.000

Significant correlations are shown in bold.

Table 2. The Variables and Their Abbreviations

Geomorphic Variables:

Relative relief - REL
Landform type - LF
Joint control of landform - JC

Structural Variables:

Mean primary spacing:
- Vertical joints - MVPS
- Horizontal joints - MHPS

Mean secondary spacing:
- Vertical joints - MVSS
- Horizontal joints - MHSS

Petrographic Variables:

Grain Size:
- Rock - MRGS
- Quartz - MQUA
- Potassium feldspar - MKSP
- Plagioclase - MPLG

Composition:
- Percent quartz - PQUA
- Percent potassium feldspar - PKSP
- Percent plagioclase - PPLG
- Percent tourmaline - PTM
- Presence/absence schorl - SCHR
- Presence/absence tourmaline veins - VEIN
- Presence/absence clay - CLAY

Rock Texture:
- Grain size distribution - GSD
- Number of megacrysts - PHEN
- Percent volume megacrysts - MEGA

Relative Relief. The correlation between relative relief (REL) and percent megacrysts (MEGA) is positive, as is that with number of megacrysts (PHEN); this latter correlation is not, however, significant. These correlations suggest that abundant megacrysts make the rock more resistant to weathering, thus tors with high relative relief are likely to be more resistant. If the megacrysts are formed by potassium metasomatism as postulated (Stone and Austin, 1961; Booth, 1968; Stone and Exley, 1969), then rock hardness may also be a factor; alteration processes have considerably hardened the Dartmoor granite in many localities. Tors with high relative relief may thus be formed of harder rock.

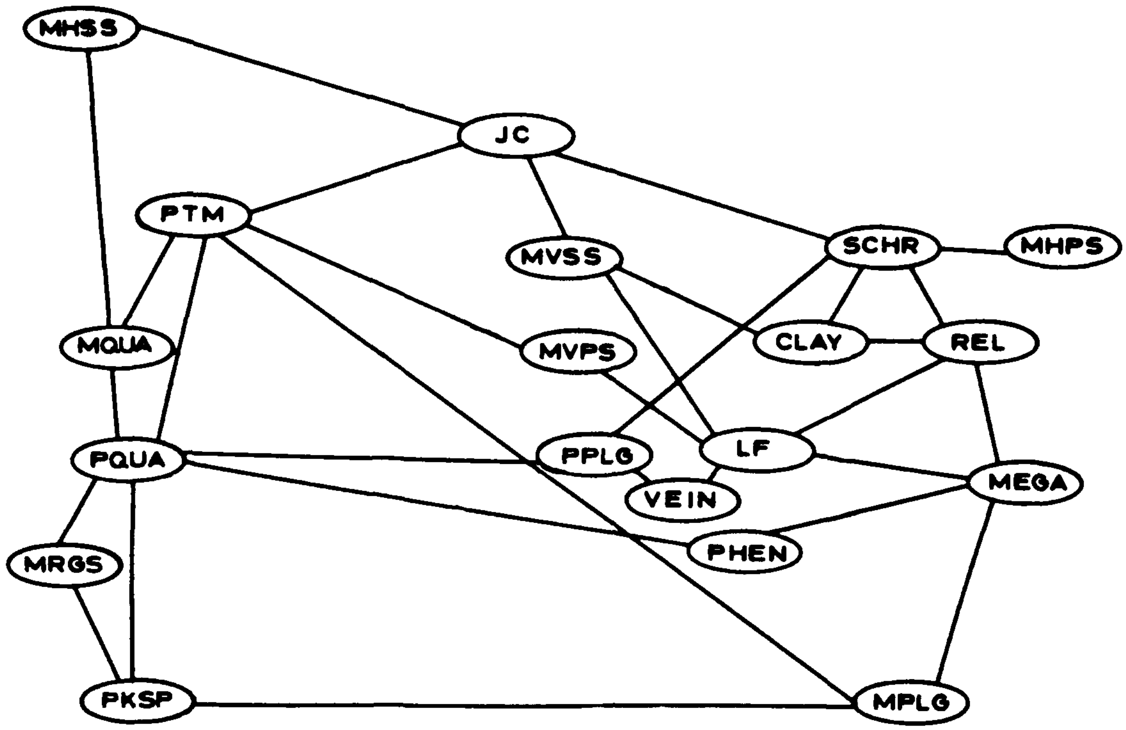

Figure 9. Correlation Bonds: Individual Variables

Although relative relief is not significantly correlated with any of the structural variables, wide vertical joint spacing (MVPS and MVSS) is positively correlated with landform (LF) and with number of megacrysts (PHEN), so there is an indirect relation. Wide vertical joint spacing is thus likely to be common in summit tors with high relative relief. The significant negative correlation between clay (CLAY) and relative relief indicates that clay is less likely to be present when relative relief is high.

Landform (LF) and relative relief (REL) are positively correlated (Table 1); summit tors thus have high relative relief, as also noted by Gerrard (1978), and spur tors have low relative relief. A positive correlation between landform and tourmaline veins (VEIN) indicates that spur tors are likely to contain tourmaline veins whereas summit tors are not (positive correlation with a binary variable indicates absence). The typically smaller size of spur tors may thus result in part from increased susceptibility to weathering in the zones containing tourmaline veins. Clay (CLAY) is positively correlated with landform as well, but not significantly; clay is thus likely to be more common in spur tors than in summit tors. Landform is positively correlated with both megacryst variables (MEGA and PHEN); summit tors are composed of highly megacrystic rock whereas spur tors are only feebly megacrystic. Landform is also positively correlated with vertical joint spacing (MVPS and MVSS): summit tors contain widely spaced vertical joints, as stated above, whereas spur tors have closely spaced vertical joints. Summit tors tend to be the largest tors on Dartmoor, indicating marked resistance to weathering and perhaps also relative youth.

Joint control. A positive correlation between joint control (JC) and secondary horizontal joint spacing (MHSS; Table 1) indicates that where joint control of tor shape is by vertical joints, or by vertical and horizontal joints combined, secondary horizontal joint spacing is wider. The correlation between joint control and secondary vertical joint spacing (MVSS) is negative, indicating that vertical joint spacing is narrow where vertical joints or vertical and horizontal joints combined control tor shape. Although the correlations with primary joint spacing (MVPS and MHPS) and relative relief (REL) are not significant, they are also positive, indicating control by horizontal joints is likely in tors with closely spaced joints and low relative relief. The positive correlation between joint control and schorl (SCHR) indicates that schorl is highly likely to occur in tors controlled by horizontal joints.

Summary. Correlations with the landform variables indicate that summit tors have high relative relief, contain abundant megacrysts, probably have no tourmaline veins, and have wide vertical joint spacing. Their large size, high relative relief, and topographic position indicate they are highly resistant to weathering. Tor shape is more likely to be controlled by vertical joints or vertical and horizontal joints combined than by horizontal joints. The large number of megacrysts suggests potassium metasomatism has occurred, and the absence of tourmaline veins suggests tourmalinzation has not. Spur tors have lower relative relief, narrow vertical joint spacing and their shapes are controlled by horizontal joints. The lower relative relief and narrower joint spacing suggest the rocks comprising spur tors are less resistant to weathering than those forming summit tors. Megacrysts are not abundant and tourmaline veins are present, suggesting that the rocks in spur tors have probably undergone tourmalinization but are not metasomatized.

Correlations with Structural Variables

The variables included in this group are mean primary vertical joint spacing (MVPS), mean secondary vertical joint spacing (MVSS), mean primary horizontal joint spacing (MHPS), and mean secondary horizontal joint spacing (MHSS); most are intercorrelated (Table 1). All the primary joint spacing variables are positively correlated, but none are correlated with secondary joint spacing of the other type; e.g. primary vertical joint spacing is not significantly correlated with secondary horizontal joint spacing. In addition, there is no correlation between secondary vertical joint spacing and secondary horizontal joint spacing. These relations suggest that: (1) primary and secondary joints in the same joint set may not necessarily be contemporaneous, (2) primary joints forming orthogonal joint sets are likely to be contemporaneous, and (3) although the primary joints are probably related, the secondary horizontal and vertical joints with orientations similar to the primary joints are not necessarily contemporaneous.

Support for (1) is provided by Segall and Pollard (1983) and Pollard and Aydin (1988) who report that short joints tend to stop propagating early on, whereas long joints continue to propagate either as individuals or by combining with pre-existing short joints. In this case, "long" and "short" are comparable to "primary" and "secondary," respectively. Several episodes of jointing in similarly oriented stress fields are implied by (3). The primary joints were long enough and well-enough established to remain unaffected or were able to continue to propagate in the same direction, perhaps in a more irregular manner, however. Existing secondary joints would remain unaffected by the new stress orientation, but those microcracks aligned properly within the new stress field would begin propagating. If the change in orientation of the new stress field were within measurement error, the situation described by (3) would occur.

Joint spacing is correlated with two of the three landform variables. Vertical joint spacing (MVPS and MHPS) is positively correlated with landform (LF), indicating wider vertical spacing occurs in summit tors and narrower spacing, in spur tors. Joint control of tor shape (JC) is negatively correlated with secondary vertical joint spacing (MVSS). Generally, the wider the horizontal joint spacing and the narrower the vertical joint spacing (vertical joints on Dartmoor are widely spaced compared to other granites), the more likely it is that tor shape will be controlled by vertical joints, either separately or in combination with horizontal joints. Correlations between landform and joint spacing and joint control and joint spacing were discussed above.

Secondary vertical joint spacing (MVSS) is positively correlated with plagioclase grain size (MPLG), and primary horizontal joint spacing (MHPS) is positively correlated with quartz grain size (MQUA). In both cases, wider joint spacing is associated with coarser grain.

With respect to composition, primary vertical joint spacing (MVPS) is positively correlated with tourmaline abundance (PTM). Wide primary vertical joint spacing is thus associated with abundant tourmaline, the hardest mineral in these rocks. Hoagland et al. (1973) provide a possible explanation for this in their work on sandstones. They determined that fracture occurs through the softer calcite cement between quartz grains, such that the larger the quartz grains were, the more irregular was the fracture path. Quartz is less hard than tourmaline; so perhaps tourmaline, by itself as well as combined with quartz in schorl, is sufficiently hard and occurs in large enough "clumps" in these granites so that a continuous fracture path cannot be maintained between individual grains. If this is the case, joints might not develop from the microcracks.

All the structural variables, except secondary vertical joint spacing (MVSS), are significantly correlated with schorl (SCHR). Wider joint spacing is thus associated with the absence of schorl, which is the opposite of what one would expect. Schorl is extremely hard and wider joint spacing would be expected in the presence of schorl, not its absence. Brammall and Harwood (1925) state that schorl is probably early magmatic, although secondary, in origin, and so is earlier than any fracturing. It is possible that because the small schorl clumps are irregularly distributed, the effect is local and this correlation is an artifact.

Summary. Correlations between the structural variables and landform indicate that summit tors contain widely spaced vertical joints and spur tors, closely spaced vertical joints. The correlation between joint spacing and joint control of tor shape indirectly indicates that summit tors are controlled by vertical joints, or by vertical and horizontal joints combined, and that horizontal joint spacing in these tors is wide. Spur tors thus contain closely spaced vertical and horizontal joints, and their shapes are controlled by horizontal joints. Other indirect correlations that support these relations are: (1) the positive correlation between joint spacing and schorl and tourmaline veins, i.e. widely spaced vertical joints occur where schorl and tourmaline veins are absent; and (2) the positive correlation between joint spacing and grain size, i.e. widely spaced joints are typical of coarse-grained rock.

Correlations with Petrographic Variables

Grain Size. The grain size variables, mean rock grain size (MRGS), mean quartz grain size (MQUA), mean potassium feldspar grain size (MKSP), and mean plagioclase grain size (MPLG), are all intercorrelated (Table 1). Except for plagioclase, grain size is negatively correlated with potassium feldspar (PKSP) and quartz (PQUA) abundances: fine grain is associated with abundant potassium feldspar and quartz. In addition, coarser-grained quartz (MQUA) and plagioclase (MPLG) are associated with higher tourmaline abundances (PTM). Because the coarser-grained quartz results from secondary growth, this correlation suggests much of the tourmaline in the granite is secondary. Brammall and Harwood (1925) indicate that it is probably late as well. A similar situation exists between plagioclase grain size and tourmaline abundance. Some plagioclase megacrysts are zoned, and there are plagioclase rims on some of the potassium feldspar megacrysts, indicating at lease some of the plagioclase is secondary and late. These somewhat inexplicable relations between the very hard and resistant tourmaline and quartz and the readily weathered plagioclase suggest that grain size may not be very important with respect to weathering in the Dartmoor granites.

Both plagioclase abundance (PPLG) and grain size (MPLG) are positively correlated with both megacryst variables (MEGA and PHEN). This correlation reflects a primary relationship within the magma chamber -- as potassium is removed to form early megacrysts, the melt becomes relatively enriched in sodium so that plagioclase feldspar is formed. There are three or four sizes of potassium feldspar megacrysts, indicating the presence of several generations. The larger megacrysts are late stage and/or metasomatic, but the smaller ones, those similar in size to plagioclase megacrysts, are early and magmatic in origin. Charoy (1986) identified similar secondary plagioclase in the Carnmenellis granite to the west (see Figure 1).

There are no significant correlations between grain size and landform (LF). However, landform is positively correlated with both megacryst variables (MEGA and PHEN), which are both positively correlated with grain size. This indirectly suggests a relation between summit tors and coarse grain. A similar relation is indicated between spur tors and finer grain. There is more evidence for such a relation in the positive correlation between grain size and wide vertical joint spacing (MVPS and MVSS): landform is positively correlated with vertical joint spacing. Summit tors thus contain widely spaced vertical joints and should be coarse grained, whereas spur tors with closely spaced vertical joints should be finer grained.

Quartz grain size (MQUA) is positively correlated with horizontal joint spacing (MHPS and MHSS), and plagioclase grain size (MPLG), with secondary vertical joint spacing (MVSS). Correlations between quartz grain size and vertical joint spacing (MVPS and MVSS), although not significant, are also positive. Coarse grain is thus again associated with wide joint spacing and finer grain, with narrow joint spacing. Thorp (1967) found a similar relation between fine grain and closely spaced joints in the Jarawa granite in Nigeria. In addition, quartz is one of the hardest minerals in these rocks (only tourmaline is harder), and as stated above with respect to relative relief, hard, resistant rock is associated with widely spaced joints. Pye et al. (1986) found this same relation in Kenyan granites. Joints on Dartmoor occasionally cut feldspar grains, but none were noted cutting quartz grains.

Plagioclase is less hard than quartz and relatively easily weathered, so the correlation between plagioclase grain size (MPLG) and wide secondary vertical joint spacing (MVSS) is puzzling. One would expect joints to be more closely spaced in rock that is more highly weathered, but this correlation suggests otherwise. This relation may reflect the influence of a third variable, such as percent megacrysts (MEGA) -- the correlation between grain size and percent megacrysts is stronger than that between grain size and vertical joint spacing (MVPS and MVSS), for instance, and megacrysts become more abundant as vertical joint spacing becomes wider.

Composition. There are two types of composition variables: modal percents and binary variables. The modal variables are percent quartz (PQUA), percent potassium feldspar (PKSP), percent plagioclase feldspar (PPLG), and percent tourmaline (PTM); and the binary variables are clay (CLAY), tourmaline veins (VEIN), and schorl (SCHR). Most of these variables are intercorrelated (Table 1). All correlations, except that between quartz and potassium feldspar, are negative. So, as quartz abundance increases, plagioclase and tourmaline abundances decrease, but potassium feldspar abundance increases. As potassium feldspar abundance increases, tourmaline and plagioclase abundances decrease. There is no significant correlation between tourmaline and plagioclase abundances.

These relations can be explained in terms of petrogenesis of the granite. With reference to the Carnmenellis granite in Cornwall, Charoy (1986) states that plagioclase and biotite formed early, followed by white mica, potassium feldspar, tourmaline, and secondary plagioclase. Quartz crystallization continued throughout. According to Brammall and Harwood (1925), with respect to the Dartmoor granite, primary tourmaline is early, but secondary tourmaline formed both early and late, and some is possibly post-magmatic. In addition, Hawkes and Dangerfield (1978) suggest potassium feldspar formed both early and late in these rocks and Zen (1988) shows that tourmaline is a product of the reaction that produces potassium feldspar. All this suggests that correlations between quartz and tourmaline and potassium feldspar should be positive, but they are not. This may be because the variable tourmaline abundance does not reflect the total amount of tourmaline in the rock: neither the tourmaline in schorl nor that filling joints is included.

With respect to the other variables, quartz (PQUA) and potassium feldspar (PKSP) behave almost identically. They are both negatively correlated with number of megacrysts (PHEN) and grain size (with the exception of potassium feldspar). As abundances decrease, the number of megacrysts increases and grain size becomes larger. The fact that quartz and potassium feldspar act together is to be expected in hydrous, peraluminous magmas with compositions near the ternary minimum such as the Cornubian granites (Tuttle and Bowen, 1958).

Plagioclase is negatively correlated with tourmaline veins (VEIN) and schorl (SCHR). As plagioclase abundance increases, both tourmaline veins and schorl are less likely to occur. Tourmaline abundance (PTM) is positively correlated with primary vertical joint spacing (MVPS): high tourmaline abundances are thus associated with wide joint spacing. This relation reflects the extreme hardness of tourmaline. Tourmaline is also positively correlated with quartz (MQUA) and plagioclase (MPLG) grain size, as well as with relative relief (REL), which were discussed previously.

Schorl (SCHR) and clay (CLAY) are significantly correlated. This relation is positive such that the two variables tend to occur together, or neither is present. This is not surprising because both result, at least in part, from the late-stage and/or post-magmatic alteration processes of tourmalinzation and kaolinization, respectively. As stated above, schorl is negatively correlated with joint control of tor shape (JC) and with horizontal joint spacing (MHPS and MHSS). Schorl is thus likely to be present when closely spaced horizontal joints control tor shape, i.e. in lamellar tors. The correlations between schorl and tourmaline veins (VEIN), which also results from tourmalinization, and clay and tourmaline veins, although not significant, are also positive. Field observations support the association between tourmaline veins and schorl, but Hawkes (1982) states they are not associated. They certainly occur together, but they may not be contemporaneous.

With respect to the geomorphic variables, the only correlations with the composition variables are with the binary variables tourmaline veins (VEIN) and schorl (SCHR). Tourmaline veins are negatively correlated with landform (LF) and with secondary joint spacing (MVSS and MHSS): tourmaline veins are thus highly likely to occur in spur tors, and to be absent in summit tors, and secondary joint spacing tends to be narrower where tourmaline veins are present.

Clay (CLAY) is negatively correlated with relative relief (REL) and secondary vertical joint spacing (MVSS): it is rare where relative relief is high and where secondary vertical spacing is wide.

These characteristics are common to summit tors, so it is likely that clay is also absent in summit tors.

Schorl (SCHR) is positively correlated with primary joint spacing (MVPS and MHPS), secondary horizontal joint spacing (MHSS), and joint control of tor shape (JC). Schorl, then, is likely to occur where joint spacing, particularly horizontal joint spacing, is narrow and where joint control of tor shape is by horizontal joints.

Rock Texture. The texture variables, number of megacrysts (PHEN), percent megacrysts (MEGA), and grain size distribution (GSD), are also intercorrelated (Table 1). Grain size distribution is positively, significantly correlated with all variables except plagioclase abundance (PPLG), indicating that the granite is typically megacrystic. Megacrystic rock is thus associated with high relative relief, summit tors and wide joint spacing. The rocks are coarse grained and contain abundant quartz, potassium feldspar and tourmaline. Tor shape is controlled by vertical joints or a combination of horizontal and vertical joints. Schorl, clay and tourmaline veins are absent. The reverse is true for equigranular rock, i.e. equigranular rock occurs in spur tors, which have low relative relief and contain closely spaced joints. The groundmass of the rock is finer grained, and quartz, potassium feldspar and tourmaline abundances are low. Tor shape is controlled by horizontal joints, and schorl, clay and tourmaline veins are likely to be present.

Both megacryst variables (MEGA and PHEN) are positively correlated with landform (LF), indicating that summit tors are likely to be strongly megacrystic, whereas spur tors are feebly megacrystic or equigranular, as noted above. The relations between these variables and relative relief (REL) were previously noted, as was the positive correlation between plagioclase grain size (MPLG) and number of megacrysts.

Number of megacrysts (PHEN) is significantly correlated with composition. As the number of megacrysts increases, quartz (PQUA) and potassium feldspar (PKSP) abundances decrease. The relation with plagioclase is the reverse; as the number of megacrysts increases, so does plagioclase abundance (PPLG). A similar relation, discussed above, exists between number of megacrysts and plagioclase grain size (MPLG). The relation between number of megacrysts and potassium feldspar relates to the total amount of potassium in the magma. Initially, some potassium went into the original, primary megacrysts, which depleted the remaining magma in potassium and limited the amount that could be used to form potassium feldspar in the groundmass. The process of removing potassium to produce megacrysts relatively enriched the melt in the components of plagioclase feldspar so that, proportionally, more groundmass plagioclase was formed. Most of the megacrysts, particularly the large ones, were thus formed later, some by recrystallization and some as a result of secondary growth on potassium feldspar crystals.

The positive correlation between number of megacrysts (PHEN) and primary joint spacing (MVPS and MHPS), also noted previously, suggests potassium metasomatism may make the rock harder and/or more resistant. Robb's (1979) trend surface analysis of composition and landform in South African granites shows that high potassium content and greater resistance to weathering are related, as does the work of Pye et al. (1984) in the Matapos Batholith in Zimbabwe. Number of megacrysts is positively correlated with tourmaline veins (VEIN) as well: as the number of megacrysts increases, tourmaline veins are less likely to be present. This relation implies that the process of megacryst formation may be independent of tourmalinization, both temporally and spatially. Reactions that produce tourmaline also produce potassium feldspar (Zen, 1988), so one would expect abundant megacrysts to be associated with tourmaline veins as well as abundant tourmaline in the rock. Neither case is true here, however.

Summary. Significant correlations between landform and the petrographic variables are few. Summit tors are strongly megacrystic, and both schorl and tourmaline veins are rare. The reverse is true for spur tors: the rocks forming spur tors are equigranular or feebly megacrystic and are likely to contain both schorl and tourmaline veins.

There are also a number of indirect relationships. Summit tors contain abundant megacrysts; both of these variables are positively correlated with coarse grain. A similar relation is indicated between spur tors and finer grain. There is additional evidence for this relation in the positive correlation between grain size and wide vertical joint spacing. Landform is positively correlated with vertical joint spacing, so summit tors which contain widely spaced vertical joints, should be coarse grained, whereas spur tors with narrow vertical joint spacing should be finer grained. In addition, the correlation between schorl and joint spacing indirectly indicates that horizontal joint spacing in spur tors should be narrow and in summit tors, it should be wide, which is in fact commonly the case. Quartz and potassium feldspar abundances are negatively correlated with number of megacrysts, which is positively correlated with landform; quartz and potassium feldspar abundances should thus be low in summit tors and high in spur tors. Coarse grain bears a similar relation with quartz and potassium feldspar abundances, strengthening this indirect relation. Finally, because plagioclase abundance is negatively correlated with tourmaline veins and schorl, plagioclase is likely to be abundant in summit tors but not in spur tors.

Summary

This analysis of correlations can be used to characterize summit and spur tors on Dartmoor. Direct relations based on significant correlations with landform and indirect relations based on correlations between other variables, one of which is significantly correlated with landform, can be used.

The significant correlations indicate that summit tors are characterized by high relative relief and wide vertical joint spacing. They contain few tourmaline veins and are usually controlled by either vertical joints alone or by horizontal and vertical joints combined. The rocks are strongly megacrystic and schorl is typically absent. Indirect relations indicate summit tors also have widely spaced horizontal joints and are composed of coarse-grained rock with abundant plagioclase and tourmaline. Quartz and potassium feldspar abundances are low, and clay is usually absent. These characteristics suggest that summit tors are highly resistant to weathering and erosion and that the rocks comprising them have undergone potassium metasomatism, but not tourmalinization or kaolinization.

The significant correlations indicate that spur tors, on the other hand, are likely to be feebly megacrystic or equigranular in texture, to have narrower vertical joint spacing, to contain both tourmaline veins and schorl, and to have lower relative relief. They are also more likely to be controlled by horizontal joints. Indirect relations suggest the rocks in spur tors contain closely spaced horizontal joints, are finer grained and contain clay. Tourmaline and plagioclase abundances are low, and quartz and potassium feldspar abundances are high. Spur tors are less resistant to weathering than are summit tors, and have most likely undergone both tourmalinization and kaolinization, but not potassium metasomatism.

Analysis of the correlation bonds between the variable categories also provides useful information. Correlation bonds, lines drawn between significantly correlated variables or groups of variables (regardless of sign), are a graphic method of representing correlations. Study of the correlation bonds (Figure 10) suggests several relations not noted above. There are no significant correlations, for instance, between the grain size and landform variables or between the joint spacing and rock texture variables. This suggests that grain size and rock texture, which is related to grain size, may be less important than other variables with respect to the landform and fracture patterns on Dartmoor. The absence of a relation, however, may result from the statistical procedure used to analyze the data. The results of this analysis clearly indicate that multiple relations exist between variables, yet calculation of correlation coefficients only addresses relations two-by-two. Multivariate procedures may well be more useful.

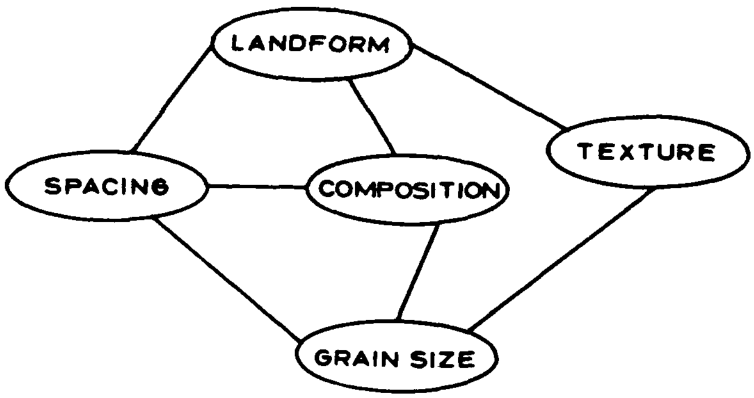

Figure 10. Correlation Bonds: Summary

MULTIVARIATE ANALYSIS

Introduction

Multivariate statistics were chosen to evaluate these data for several reasons. Although it is likely that only a few of the factors that might affect tor shape are significant, it is difficult to determine which are the important ones. Using other procedures, such as linear regression or analysis of correlations, variables can be evaluated two-by-two, but such approaches do not allow multiple interrelationships to be readily untangled. In addition, many such procedures accept only ratio and interval variables: many of the variables used in this study are binary, nominal or ordinal. Certain multivariate statistical procedures allow all types of variables to be evaluated at the same time.

Principal components analysis and principal coordinates analysis were the ordination procedures tested. Principal coordinates analysis was selected because, unlike principal components analysis, (1) it accepts nominal and ordinal variables; (2) it is distribution free (many of the variables have lognormal or power-law distributions); (3) it is a Q-mode procedure that "views" the data from the perspective of the sample site rather than from that of the variable, which is more useful for the purposes of this study; and (4) the results using principal coordinates analysis were more reasonable in a geologic context than those using principal components analysis.

Both hierarchical and non-hierarchical classifications were tested. A non-hierarchical classification was selected for many of the same reasons that principal coordinates analysis was chosen: (1) it allows inclusion of nominal and ordinal variables; (2) it accepts variables that are not normally distributed; and (3) the data set contains little structure, making an hierarchical classification inappropriate.

Principal Coordinates Analysis

The six most important coordinates, accounting for 54.6% of the total variance, were identified by plotting the latent vectors (eigenvectors) against latent roots (eigenvalues). Snedecor's F-statistic was used to identify the important variables associated with each coordinate. High, positive F-values equate to heavy loading; the higher the F-value and the heavier the loading, the larger the part that variable plays in defining the coordinate. The high loadings were sufficiently obvious so that identification of the important variables was quite simple. The variables defining the six coordinates are

1. Mean vertical primary joint spacing.
   Mean vertical secondary joint spacing.
   Secondary horizontal/vertical joint spacing ratio.
   Presence or absence of tourmaline veins.

2. Number of megacrysts.
   Mean plagioclase grain size.

3. Quartz abundance.
   Plagioclase abundance.

4. Landform.
   Mean vertical primary joint spacing.

5. Presence or absence of schorl.

6. Mean potassium feldspar grain size.

Frequency histograms for the eigenvectors for each sample site were generated for each coordinate (Figure 11). The sample sites tended to occur in groups, and the "quality" of the pertinent variables was identified using the end member groups. For instance, if the coordinate were identified as grain size, the ranks of the grain sizes of the sample sites in the end member groups determined which end of the coordinate represented coarse grain and which fine grain. These groups are described below beginning with the group with the highest positive values; the highest numbered group contains the sites with the lowest negative values. Analysis and interpretation of these results follows a similar description of the results of classification.

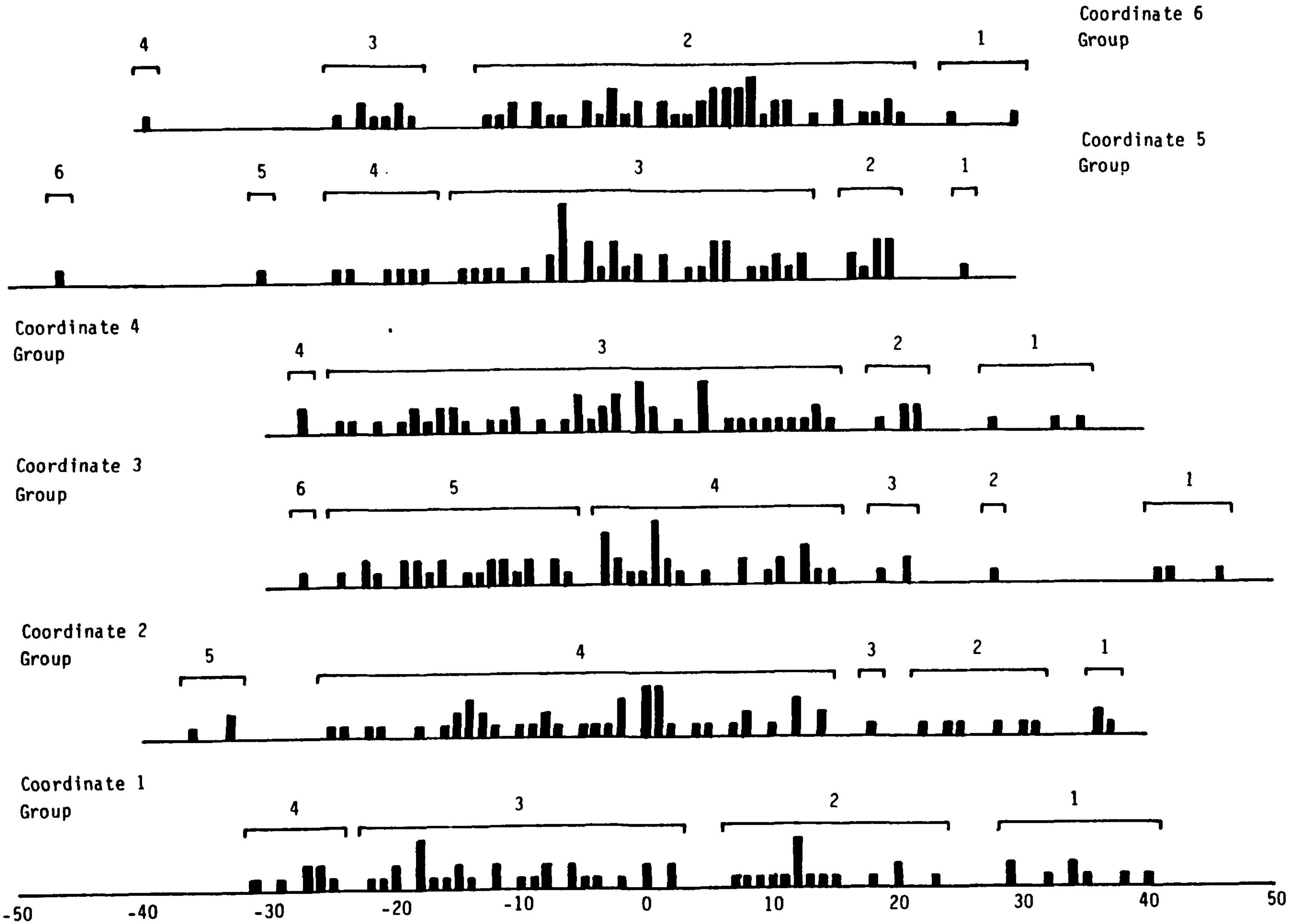

Figure 11. Distribution of Sample Sites Along the Six Principal Coordinates

There are four groups of sample sites along *Coordinate 1* (see Figure 12), which represents vertical joint spacing, the secondary joint spacing ratio, and tourmaline veins. Group 1 represents wide vertical joint spacing, low secondary ratios, and no tourmaline veins. These sites occur primarily in the eastern and northeastern parts of the moor. Many lamellar tors, such as Great Links Tor and Branscombe's Loaf, are included. Groups 2 and 3 represent intermediate values for all variables. Group 2 forms a V-shaped pattern, with the open part of the V facing west, and includes the coarsest-grained tors, e.g. Down and Oke Tors. Group 3 is concentrated in the west-central part of the moor and includes many of the reddened or altered tors, such as Sharp and Doe Tors. Group 4 represents intermediate vertical joint spacing, high secondary joint spacing ratios, and tourmaline veins. These tors occur mainly around the edges of the granite, along escarpments or near steep slopes, but are not present in the northeast. Examples include Buckland Beacon and Mel Tor, high above the River Dart.

There are five groups of sample sites along *Coordinate 2* (Figure 13), which represents number of megacrysts and plagioclase grain size. Group 1 occurs in the north and northwest and represents no megacrysts and fine-grained plagioclase. Groups 2, 3 and 4 all represent intermediate values for both variables in increasing order. Although Group 2 occurs mainly in the north and northwest, it also includes Hen Tor in the south and the western block of Haytor Rocks in the east. These tors are located adjacent to steep slopes and/or on escarpments. Group 3 is comprised only of Little Tor (Hemery, 1983), a small, lamellar tor south of West Mill Tor, unnamed on the Ordnance Survey maps. Group 4 occurs throughout the moor, being least common in the north. Group 5 is very small, extending from east to west across central Dartmoor. It represents coarse-grained plagioclase and abundant megacrysts. Group 5 tors are located on or form domes.

The seven groups along *Coordinate 3* (Figure 14) are not as distinct as those along Coordinates 1 and 2 and are also not as clearly defined with respect to the variables. Coordinate 3 represents quartz and plagioclase abundances. Group 1, characterized by very low quartz abundances and abundant plagioclase, occurs in the extreme northern and southern parts of the moor. Belstone Ridge Tor, unnamed on the topographic maps, comprises Group 2. It is the northern-most tor on the ridge upon which Belstone Tor is located. Groups 3, 4 and 5 represent intermediate to high plagioclase abundances and low to intermediate quartz abundances in decreasing and increasing order, respectively. Group 3 occurs in the extreme south and in the east; Group 4 is present mainly in the east, but also occurs in the south and northwest; and Group 5 occurs everywhere except in the south. Groups 6 and 7 both represent intermediate quartz and plagioclase abundances. Group 6 occurs throughout the moor; Higher White Tor in the central part of Dartmoor comprises Group 7.

There are four groups along *Coordinate 4*, which represents landform and primary vertical joint spacing (Figure 15). Group 1 represents intermediate to wide joint spacing and spur tors. The three tors, Brat Tor, Hart Tor and Emsworthy Rocks, exhibit no distinct spatial pattern. Emsworthy Rocks, located about 1 km west of Haytor Rocks, is unnamed on the topographic maps; this name was used by Hemery (1983). Groups 2 and 3 represent intermediate joint spacing and include all three landform types. All valleyside tors are included in these two groups. Group 2 occurs in the south, in the Dart valley, in the northeast and in the north-central part of Dartmoor. Except for Elsford Rock, these tors are found near the granite boundary. Group 3 occurs throughout the moor. Group 4 represents narrow joint spacing and summit landforms. It is composed of the fine-grained exposures at West Mill Tor and Haytor Rocks.

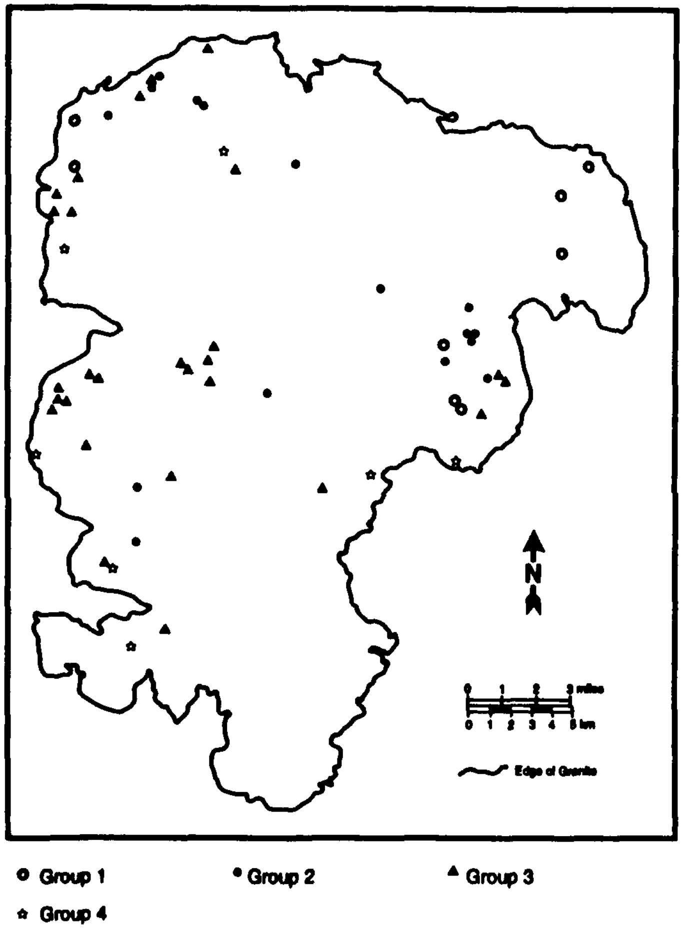

Figure 12. Spatial Distribution of Sample Sites Along Coordinate 1.

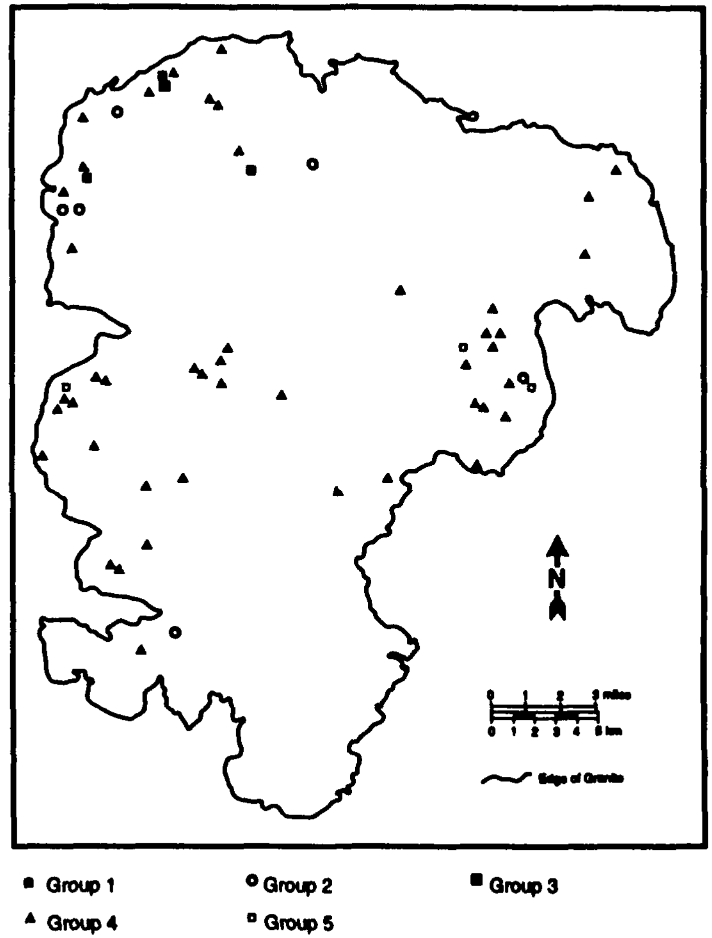

Figure 13. Spatial Distribution of Sample Sites Along Coordinate 2.

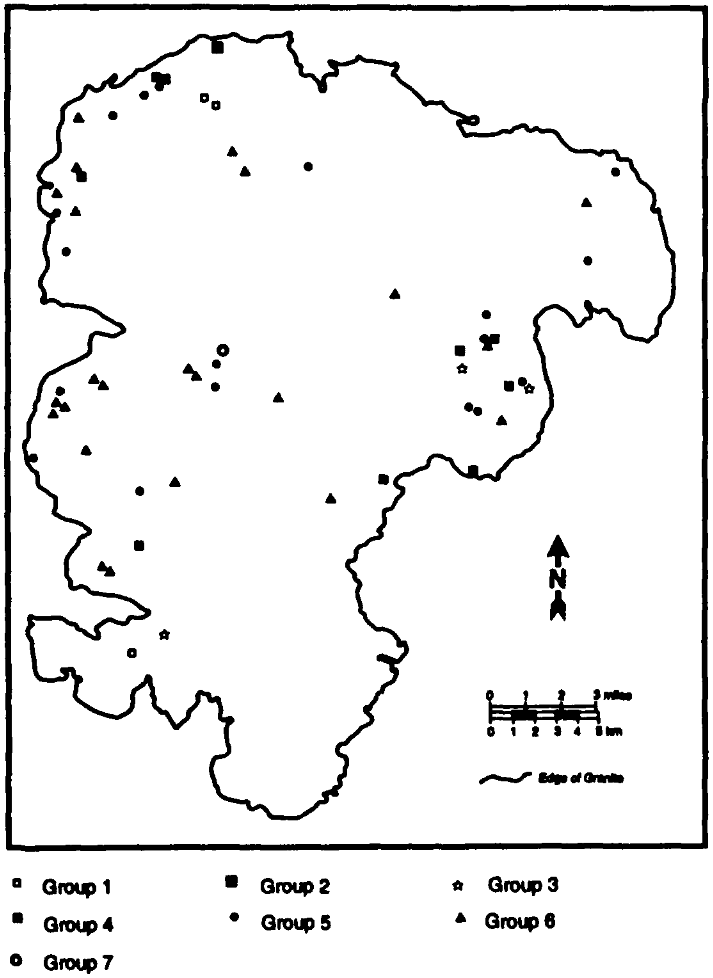

Figure 14. Spatial Distribution of Sample Sites Along Coordinate 3.

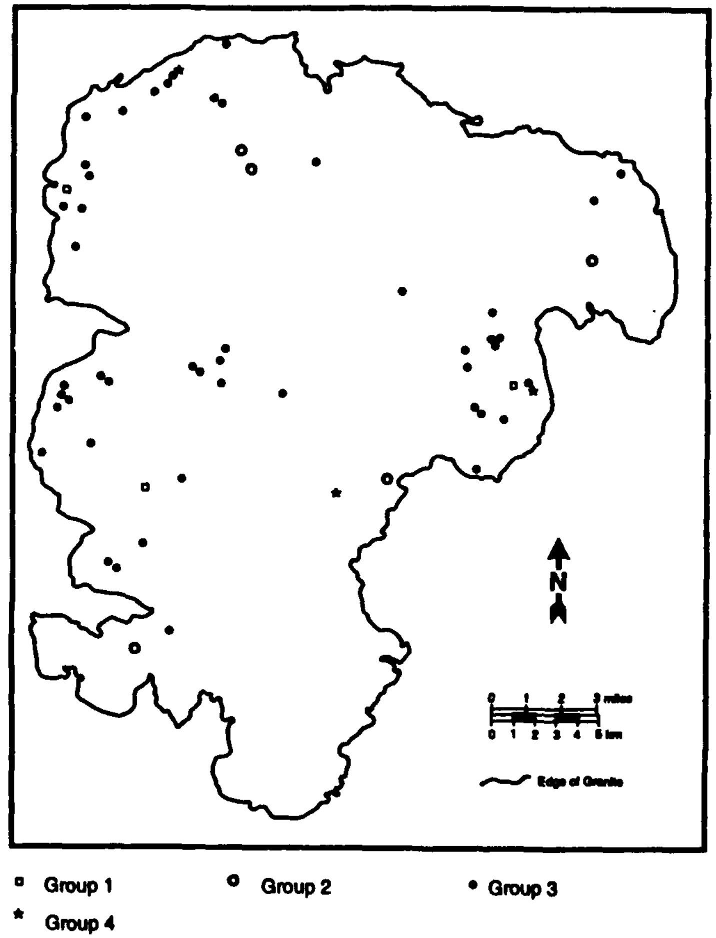

Figure 15. Spatial Distribution of Sample Sites Along Coordinate 4.

The sample sites along *Coordinate 5*, which represents schorl, comprise six groups (Figure 16). The members of Groups 1 and 2 contain schorl. Longaford Tor alone comprises Group 1. Group 2 occurs in the west, the west-central and southern parts of Dartmoor, forming a north-northwest-trending band from Hen Tor to Sharp Tor. Groups 3 and 4 occur throughout the moor and many of the tors contain schorl. Group 3 is concentrated in the northern half of the moor, and Group 4 occurs throughout the moor except in the northeast. Groups 5 and 6 both occur in the east and neither contains schorl. Additionally, each consists of only one tor: Group 5, of the small tor southeast of Hound Tor and Group 6, of the fine-grained part of Haytor Rocks.

Coordinate 6 represents potassium feldspar grain size (Figure 17). Groups 1 and 2 have intermediate grain size. Group 1 occurs in the east and the extreme north. Both members, Buckland Beacon and Belstone Ridge Tor, are located near the edges of the granite. Group 2, the largest group, is present throughout the moor. Group 3, restricted to the western and central parts of Dartmoor, is most common in the southwest. It represents medium- to coarse-grained potassium feldspar. Group 4 consists of the eastern block of Great Staple Tor and represents coarse-grained potassium feldspar.

The values for each sample site were plotted on scattergrams for all combinations of coordinates. As expected, the most easily interpreted and thus "best" scattergrams are those with the lower-numbered coordinates forming the axes, i.e. Coordinate 1 vs. Coordinate 2. The scattergrams were used to aid interpretation of the classification and are discussed below.

Non-hierarchial Classification

Each classification procedure produces an optimum classification for a given number of clusters that is chosen by the user. For instance, if the user wishes to evaluate a maximum of four clustering levels, the program will produce the most distinct combinations for groups of four, three, two and one clusters. "Optimum" is defined in terms of the clustering algorithm. For example, if a distance measure is used, best would be the smallest (or largest) distance between members of a given cluster and the greatest (or least) distance between clusters. To determine the most appropriate clustering level for this classification, the clustering criterion or coefficient for each of 10 clustering levels was plotted on semilog paper. The points that plotted off the line formed by the majority of the points identified the optimum clustering levels; in this case, the five-cluster level was optimum.

The sample sites comprising each cluster are shown in Table 3. The variables that define the six coordinates were used to define the clusters. Beneath each variable, the ranks of each sample site for that variable were recorded. The ranks in each column were evaluated to identify any pattern that might exist. Cluster 4 is shown as an example in Table 4. Low ranks are low values and high ranks are high values. All sample sites in Cluster 4 contain schorl, so that cluster represents the presence of schorl. The ranks for quartz abundance are low for most of the sample sites, so the rocks in these tors can also be described as having low quartz abundances. The variables describing each cluster defined by this procedure are shown in Table 5.

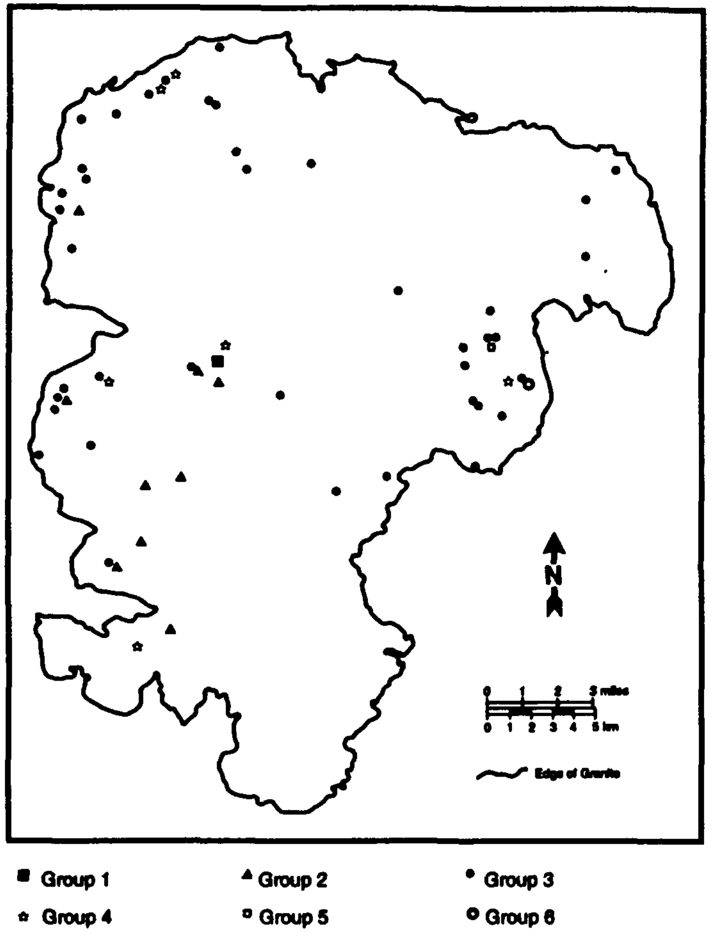

Figure 16. Spatial Distribution of Sample Sites Along Coordinate 5

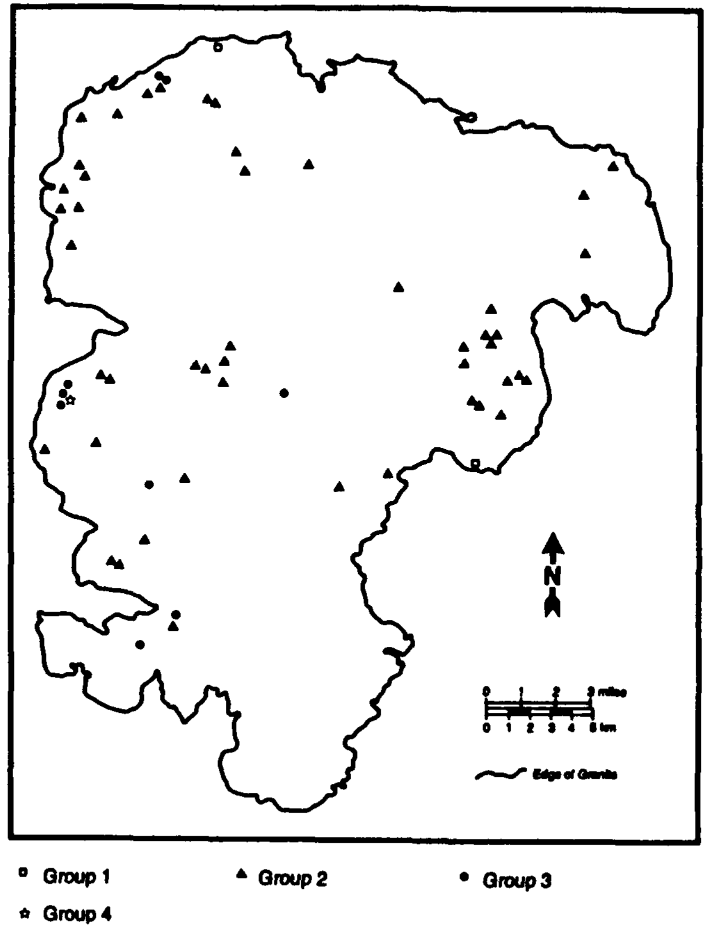

Figure 17. Spatial Distribution of Sample Sites Along Coordinate 6

Table 3. Cluster Members

Cluster	Sample sites
1	Bell Tor, Roos Tor, Little Trowlesworthy Tor, Mel Tor, the main block of West Mill Tor, the pinnacle and eastern block of Great Staple Tor, the eastern block of Haytor Rocks, and the western-most block of Great Mis Tor
2	Little Tor, Blackingstone Rock, Heltor, Elsford Rock, Emsworthy Rocks, Scorhill Tor, Hookney Tor, Bellever Tor, Branscombe's Loaf, Lower Dunna Goat, Higher White Tor, Hart Tor, Great Links Tor, Brat Tor, Watern Tor, Black Tor, and the small tor southeast of Hound Tor
3	The fine-grained parts of West Mill Tor and Haytor Rocks
4	Honeybag Tor, Hayne Rocks, Down Tor, and both blocks of Pil Tor, Oke Tor and Hound Tor
5	Yes Tor, South Hessary Tor, Combestone Tor, Belstone Ridge Tor, Middle Staple Tor, Littaford Tors, Hen Tor, Longaford Tor, Pew Tor, Wild Tor, Great Mis Tor, Ger Tor, King's Tor, Rippon Tor, Buckland Beacon, Sharp Tor, Doe Tor, the northwestern and main blocks of Sheeps Tor and the northern and eastern blocks of the Beardown Tors

Table 4. Rank and Binary Values for the Samples Sites in Cluster 4

Sample Site	PHEN	SCHR	MKSP	MPLG	MVPS	MVSS	SHVR	VEIN	LF	PQUA	PPLG
Honeybag Tor	47.5	Y	58	55	5	35.5	31	N	Su	14.5	53
Hound Tor (N)	47.5	Y	25.5	51	11	25	36	N	Su	1	56
Hound Tor (S)	38	Y	10.5	23	37	39	21.5	N	Su	40	39
Hayne Rocks	53	Y	24	46	32	32	36	N	Su	19	34
Pil Tor (N)	40	Y	43.5	48.5	29	37	17.5	N	Su	5.5	31
Pil Tor (S)	40	Y	43.5	48.5	40	40.5	21.5	N	Su	5.5	31
Oke Tor (N)	11	Y	48.5	23	26	35.5	25.5	N	Su	2.5	57.5
Oke Tor (S)	11	Y	48.5	23	44	51	29.5	N	Su	2.5	57.5
Down Tor	47.5	Y	47	50	31	23	42	N	Su	11.5	28

Table 5. Cluster Descriptors

Cluster	Descriptors
1	No valleyside tors Low to intermediate quartz abundance Tourmaline veins No schorl Medium- to coarse-grained feldspar Intermediate to high numbers of megacrysts Narrow to intermediate vertical joint spacing Medium to high secondary joint spacing ratio
2	Low to intermediate quartz abundance Low to intermediate plagioclase abundance No tourmaline veins Fine- to medium-grained feldspar Wide vertical joint spacing Low secondary joint spacing ratio
3	Summit tors Abundant quartz Intermediate plagioclase abundance No tourmaline veins Schorl Fine-grained feldspar No megacrysts Narrow vertical joint spacing
4	Summit tors Low quartz abundance Intermediate to abundant plagioclase No tourmaline veins Schorl Intermediate- to coarse-grained feldspar Intermediate to abundant megacrysts Intermediate vertical joint spacing Intermediate secondary joint spacing ratio
5	No spur tors Low to intermediate plagioclase abundance Tourmaline veins Fine- to medium-grained feldspar Few megacrysts Narrow to intermediate vertical joint spacing Medium to high secondary joint spacing ratio

The clusters were also mapped so that spatial relations could be evaluated: most of the clusters have distinct spatial patterns (Figure 18). *Cluster 1* occurs mainly south of a line between Great Mis Tor and Bell Tor. The tors in this cluster tend to be very coarse grained, e.g. the eastern block of Haytor Rocks and Roos Tor, and many, such as Mel Tor and Great Mis Tor, are associated with precipitous slopes. *Cluster 2* occurs mainly in the east, northeast, north-west and north-central parts of the moor. No tors in this group occur in the west and they are sparse in the south and central areas as well. This cluster includes all the lamellar tors, i.e. Great Links Tor, Branscombe's Loaf, Watern Tor, Little Tor and Blackingstone Rock, as well as those that are low and flattish, such as Scorhill Tor and Elsford Rock. *Cluster 3*, comprised of the fine-grained parts of West Mill Tor and Haytor Rocks, has no spatial pattern. *Cluster 4* occurs mainly in the east, with one member north and another south. Many of the avenue tors, e.g. Pil Tor, Hound Tor and Hayne Rocks, are in this group, as well as those with very coarse grain, e.g. Oke Tor and Down Tor. An avenue tor consists of two large blocks with a wide, linear space between the blocks (see Figure 6A). Although *Cluster 5* occurs everywhere except in the northeast, it is most common in the south, west and central parts of Dartmoor. This group contains most of the altered or reddened tors, e.g. Middle Staple Tor, Hen Tor, Sheeps Tor, Sharp Tor and Doe Tor; the domical tors, e.g. Yes Tor, Longaford Tor, Sheeps Tor, Great Mis Tor and Rippon Tor; and the blocky ones, e.g. South Hessary Tor, Combestone Tor and Wild Tor.

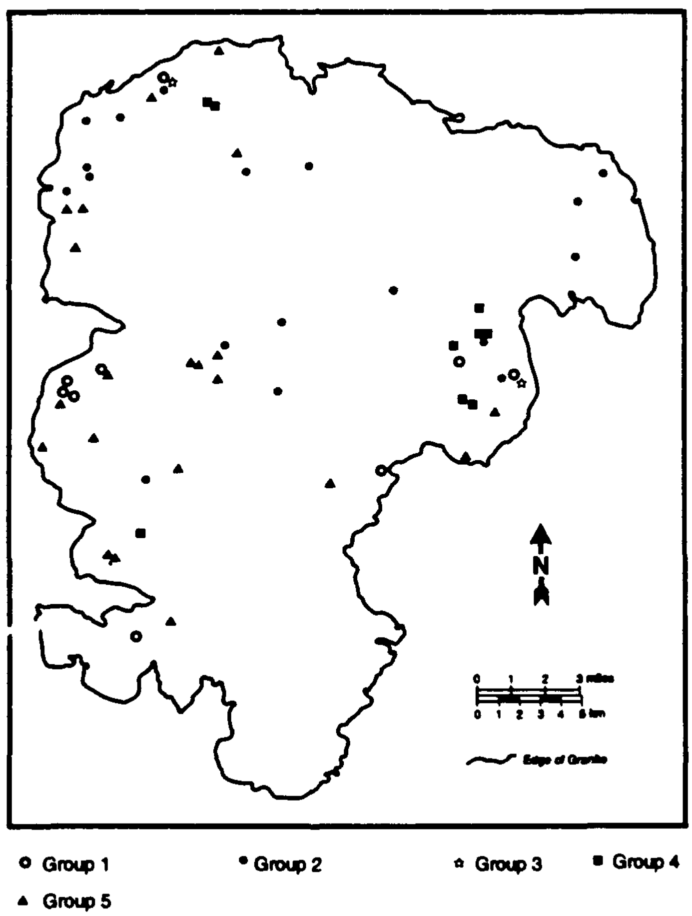

Figure 18. Spatial Distribution of the Five Clusters

Comparison of Results

The classification was superimposed on the coordinate scattergrams described previously and each quadrant was labelled, i.e. Coordinate 1 has low secondary joint spacing ratios at the negative end and high ratios at the positive end, and Coordinate 2, coarse grain at the negative end and fine grain at the positive end. Sample sites in the lower left quadrant where both coordinates are negative would have coarse grain and low secondary ratios, and so on. The descriptors for each cluster were compared to those for each quadrant, and if they agreed, the descriptors for that group of sample sites were considered reliable. If they did not, only descriptors common to both procedures were accepted. The scattergrams showing Coordinate 1 plotted against each of the other coordinates comprise Figures 19 through 23.

The principal coordinate and cluster descriptors for Cluster 1 are in good agreement. They indicate that the tors in *Cluster 1* are characterized by medium to high numbers of megacrysts, low to intermediate quartz abundances, medium- to coarse-grained feldspar, narrow to intermediate vertical joint spacing, and medium to high secondary joint spacing ratios. They contain tourmaline veins, but generally no schorl, and are mainly summit tors, although spur tors are present as well. There is a discrepancy, however, with respect to plagioclase: the scattergrams indicate these tors contain intermediate amounts, whereas the actual abundances are either high or low; the mean would of course be intermediate.

The descriptors for the tors in *Cluster 2* are also in good agreement. These tors are characterized by fine- to medium-grained feldspar, wide vertical joint spacing, low secondary joint spacing ratios, generally no tourmaline veins, and low to intermediate quartz abundances. As with Cluster 1, there is a discrepancy with respect to plagioclase. The scattergrams indicate intermediate to abundant plagioclase, whereas there are in fact only small to intermediate amounts in the rocks forming these tors.

There are some problems with *Cluster 3*, the two fine-grained sites at Haytor Rocks and West Mill Tor. Descriptors common to the scattergrams and the cluster analysis for these exposures are: equigranular texture, fine-grained plagioclase, and narrow vertical joint spacing. Both are parts of summit tors. The scattergrams, however, suggest that there is no schorl, when in fact there is, and that potassium feldspar is coarse grained, when it is in fact the finest grained of all. In addition, descriptors differ with respect to quartz and plagioclase abundances, tourmaline veins, and the secondary joint spacing ratios. Quartz is in fact abundant; plagioclase and the secondary ratios are intermediate; and there are no tourmaline veins. The discrepancies may occur because these sample sites are so very different from all other sample sites in most respects and because, although also different from each other, these differences are minor when compared to those with the other 56 sites.

Agreement between the cluster and scattergram descriptors is much better for the tors of *Cluster 4*, which are characterized by medium to high numbers of megacrysts, medium- to coarse-grained feldspar, intermediate vertical joint spacing, low quartz abundances, and intermediate to high plagioclase abundances. There are no tourmaline veins, but shorl is abundant. Most are summit tors. The only disagreement among descriptors is with respect to the secondary joint spacing ratios; the scattergrams suggest they are low, whereas they are in fact intermediate.

Finally, there is also good agreement between descriptors for *Cluster 5* tors, which are characterized by few megacrysts, fine- to medium-grained feldspar, narrow to intermediate vertical joint spacing, medium to high secondary joint spacing ratios, the presence of tourmaline veins, and low to intermediate plagioclase abundances. The tors occur mainly on summits, but this cluster also includes almost all valleyside tors. The scattergrams are unclear with reference to schorl; some show tors in this cluster containing schorl, whereas others do not. Two thirds of the sites do in fact contain schorl.

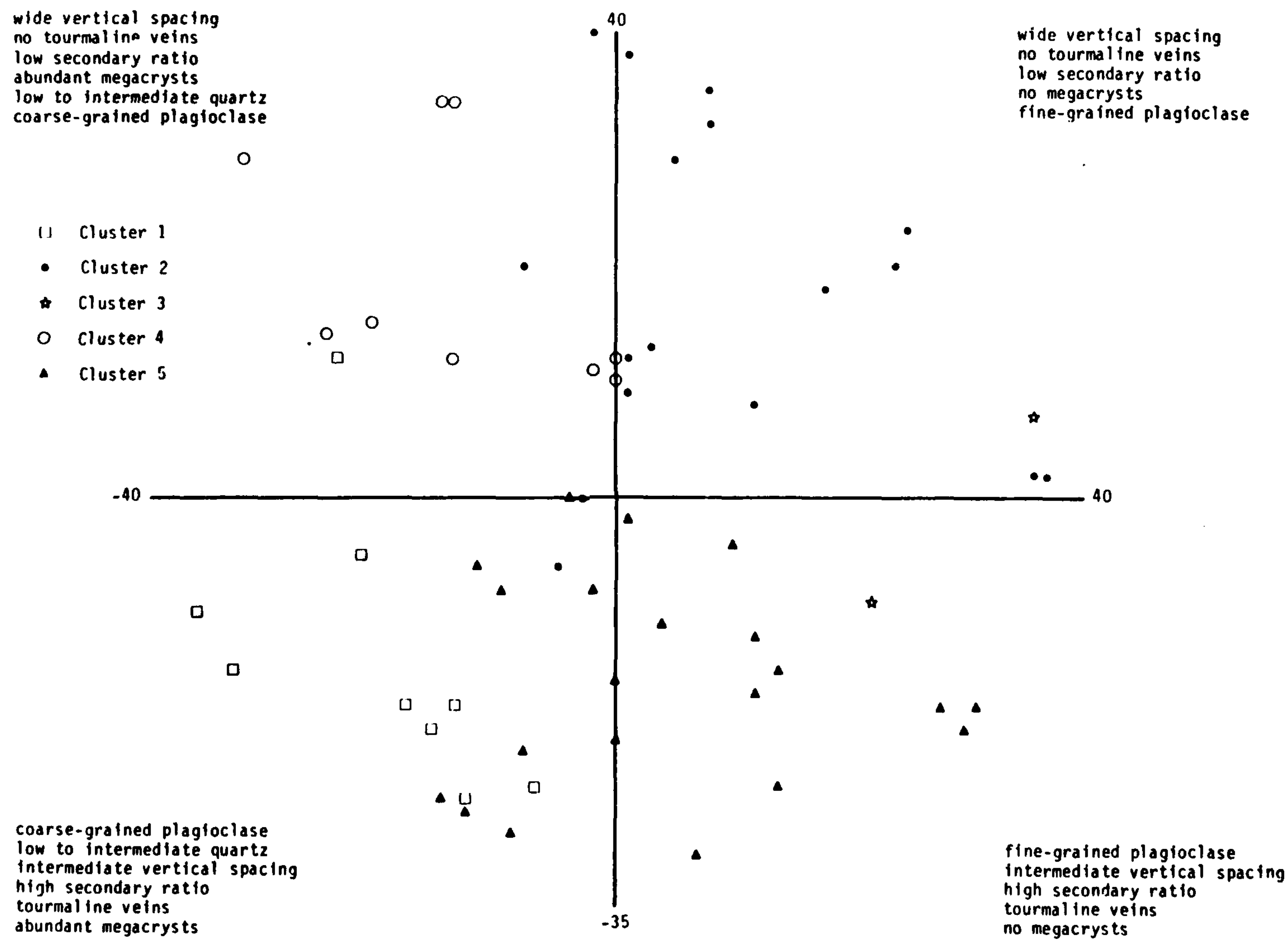

Figure 19. The Classification Laid Over Coordinates 1 (y-axis) and 2 (x-axis)

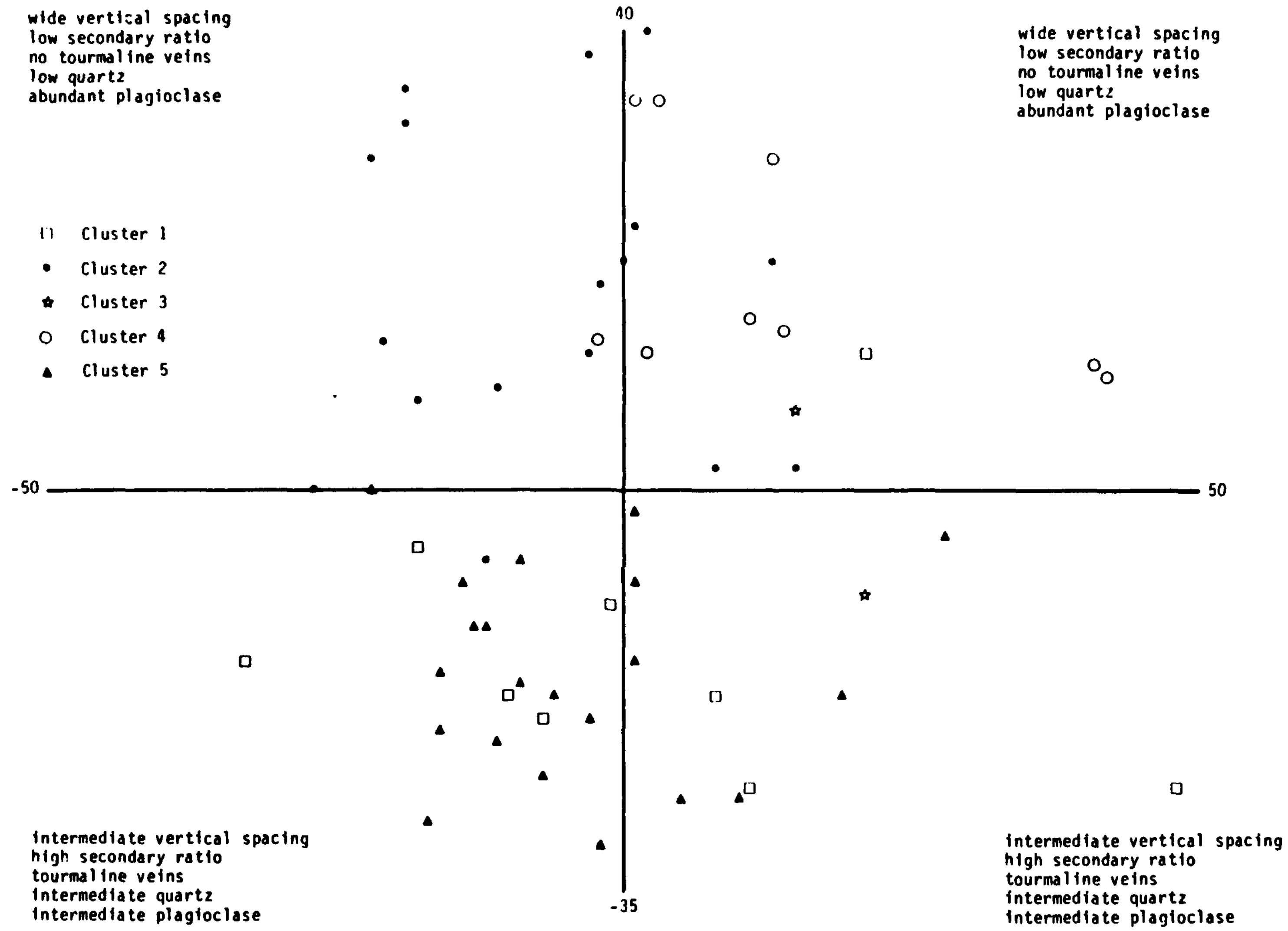

Figure 20. The Classification Laid Over Coordinates 1 (y-axis) and 3 (x-axis)

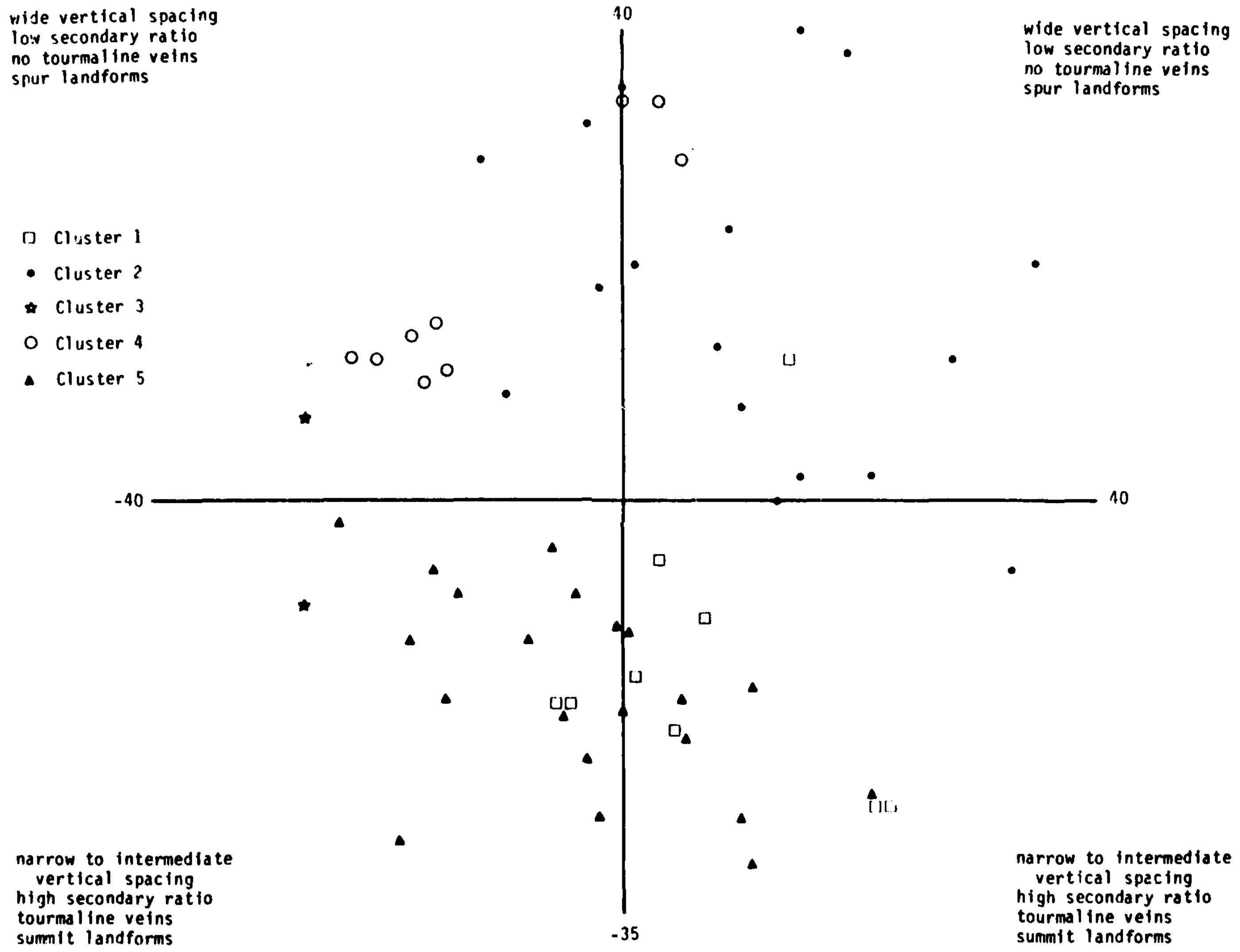

Figure 21. The Classification Laid Over Coordinates 1 (y-axis) and 4 (x-axis)

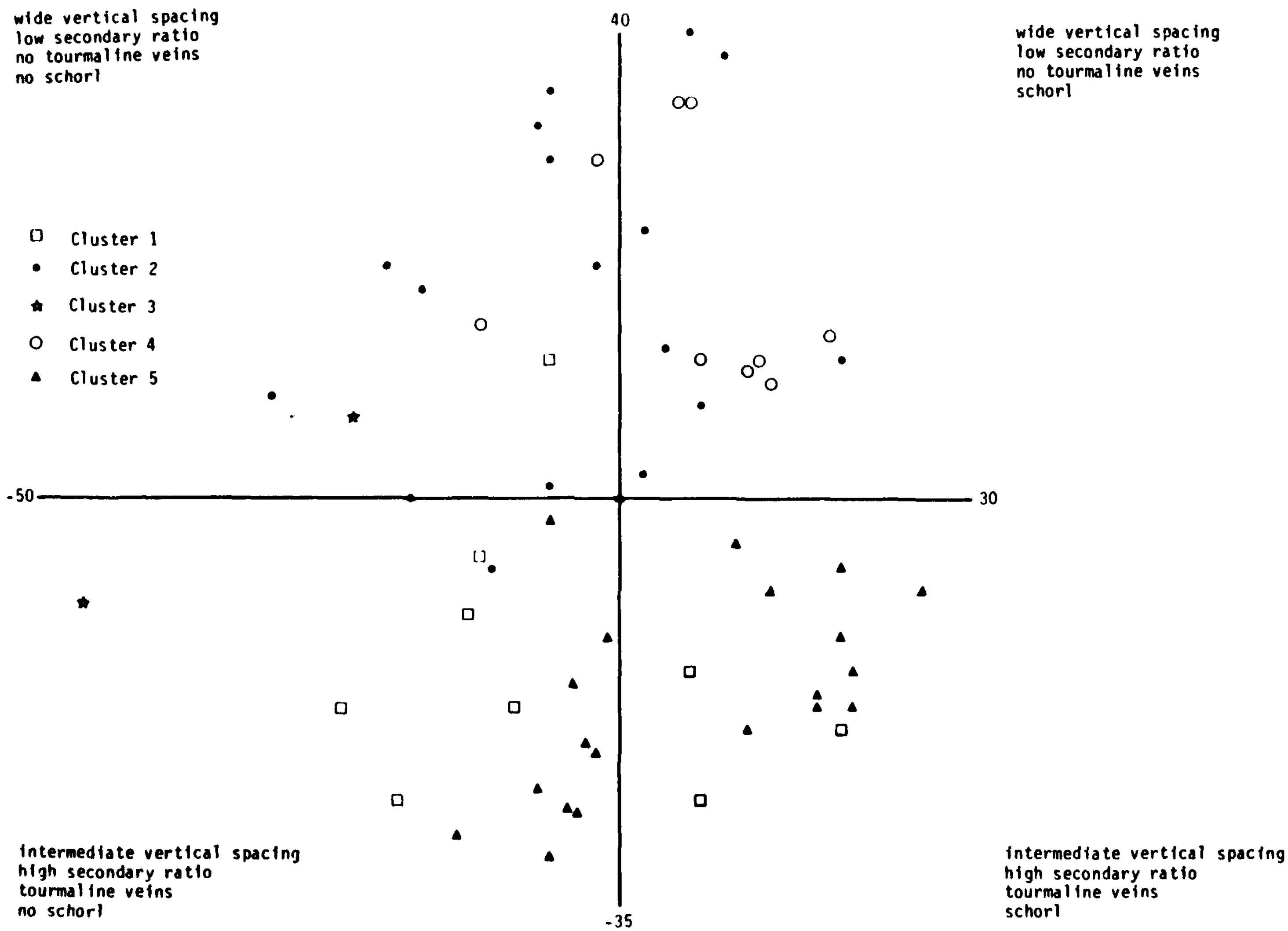

Figure 22. The Classification Laid Over Coordinates 1 (y-axis) and 5 (x-axis)

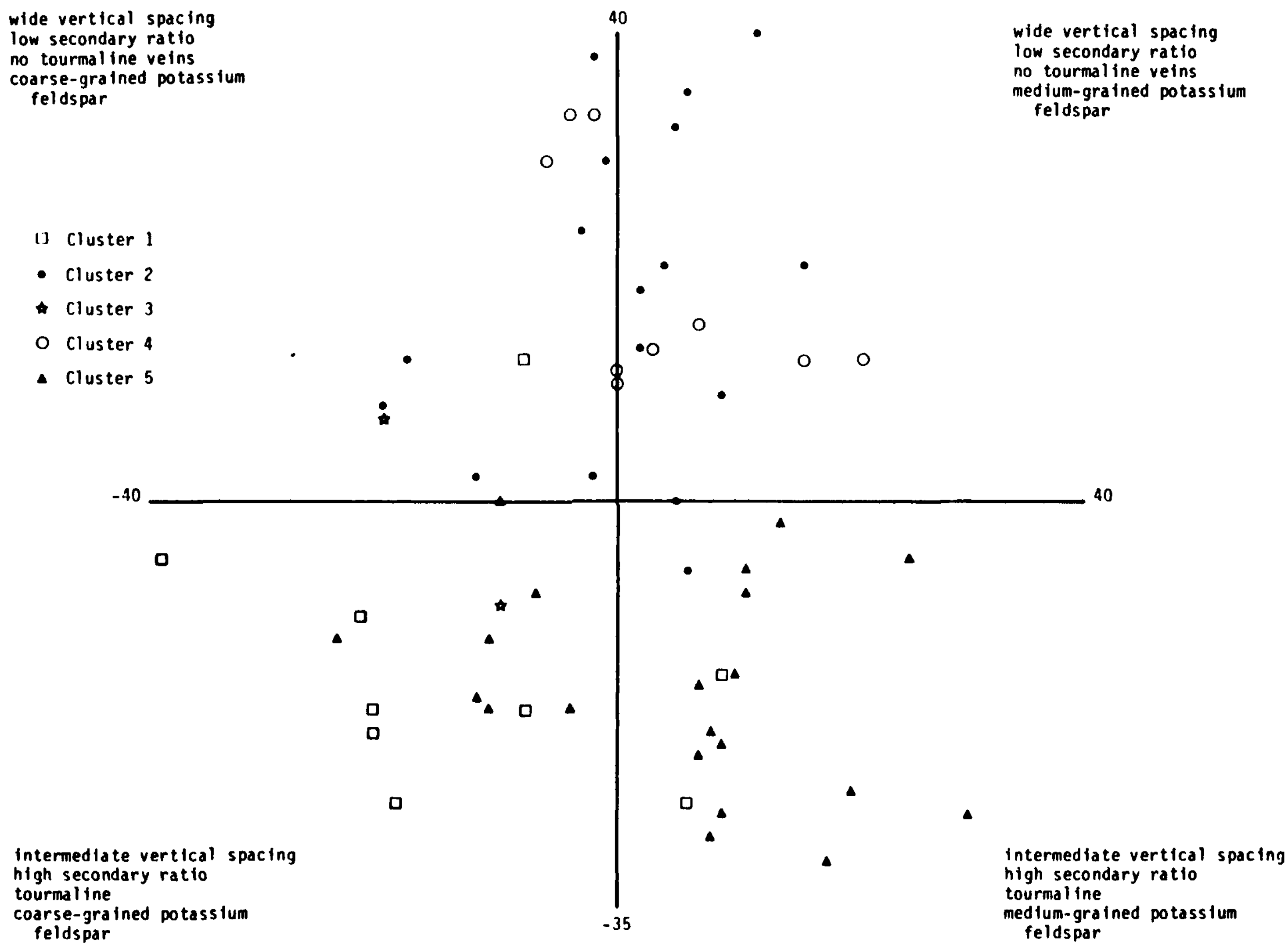

Figure 23. The Classification Laid Over Coordinates 1 (y-axis) and 6 (x-axis)

Statistical Significance

One of the problems with the multivariate procedures used here is that the results are not amenable to testing for statistical significance. Consequently, the joint spacings for the sample sites in each group along each coordinate and in each cluster were determined so that joint spacing frequency distributions for the clusters and coordinates could be compared and tested statistically. The joint spacings were tabulated and plotted on frequency histograms, and the frequency distributions were compared using chi square (Ehlen, 1991). All significant differences are at the 95% level of confidence. There is, unfortunately, some redundancy in this procedure in that joint spacing is also a variable used in the multivariate analyses.

Principal Coordinates Analysis

Chi square was used to evaluate the differences between the 256 pairs of distributions that occur along the six coordinates. Of these, 107, or 41.8%, are significantly different. Table 6 shows the number of significant relations between the groups along each coordinate and the number and kind of significantly different relation.

For *Coordinate 1*, 67% of the possible group combinations are significantly different, a total of 12 significant relations. For groups 1 and 4, and 2 and 4, all relations, except those for primary horizontal joint spacing, are significant. For groups 1 and 3, only secondary joint spacing distributions are significantly different, but for groups 3 and 4, all joint spacing distributions are significantly different. Eight of the twelve significant relations (66.7%) are between secondary joint distributions and seven (58.3%) are between vertical joint distributions only.

Table 6. Significant Differences Between Groups Along Coordinates

Coordinate	Significant Relations	Type
1	12 (67%)	8 (67%) between secondary joint distributions 7 (58%) between vertical joint distributions
2	15 (70%)	9 (60%) between secondary joint distributions 9 (60%) between vertical joint distributions
3	25 (65%)	18 (72%) between secondary joint distributions 16 (64%) between vertical joint distributions
4	15 (83%)	9 (60%) between secondary joint distributions 8 (53%) between vertical joint distributions
5	25 (60%)	16 (64%) between secondary joint distributions 14 (56%) between vertical joint distributions
6	15 (83%)	9 (60%) between secondary joint distributions 9 (60%) between vertical joint distributions

For *Coordinate 2*, 70%, or 15, of the possible group combinations are significantly different. For groups 1 and 5, both secondary joint spacing distributions are significantly different; but, for groups 1 and 3, only the secondary vertical joint spacing distributions are significantly different. Primary vertical joint spacings are significantly different for groups 1 and 4, but both vertical joint distributions are for groups 4 and 5. Both vertical joint distributions and the secondary horizontal joint spacing distribution are significantly different for groups 3 and 4, and differences between both horizontal distributions are significant for groups 2 and 5. For groups 2 and 3, all distributions are significantly different. Nine of the fifteen significant relations, or 60%, are between secondary joint spacing distributions; 60% of the significant comparisons are between vertical joint distributions as well.

For *Coordinate 3*, the 25 significant relations represent 65% of the possible combinations. For groups 5 and 6, 5 and 7, and 6 and 7, all relations except those for primary horizontal joint spacing are significant. For groups 2 and 5 and 2 and 6, both secondary joint spacing distributions are significantly different. Secondary vertical joint distributions are significantly different for groups 1 and 7, 3 and 4, 4 and 6, and 4 and 7; and for groups 1 and 5 and 1 and 6, the secondary horizontal joint spacing distributions are significantly different. Both vertical joint distributions were significantly different for groups 4 and 5; and for groups 3 and 7, all distributions are significantly different. Eighteen of the twenty-five significant relations (72%) are between secondary joint spacing distributions, and sixteen (64%) are between vertical joint distributions.

For *Coordinate 4*, 83%, or 15, of the possible combinations are significantly different. For groups 2 and 4, only secondary joint spacing distributions are significantly different, but for groups 1 and 3, 2 and 3, and 3 and 4 all distributions are significantly different. Only the distributions for secondary vertical joint spacing are significantly different for groups 2 and 4. Nine of the fifteen significant relations, or 60%, are between secondary joint spacing distributions, and eight, or 53%, are between vertical joint distributions.

For *Coordinate 5*, the 25 significant relations represent 60% of the possible combinations. Secondary joint spacing distributions are significantly different for groups 1 and 2, 2 and 5, and 2 and 6; but for groups 1 and 4, only secondary vertical joint distributions are significantly different. For groups 3 and 5, both vertical joint spacing distributions are significantly different, and all distributions are significantly different for groups 1 and 3, 2 and 3, 3 and 4, and 3 and 6. Sixteen of the twenty-five significant relations (64%) are between secondary joint spacing distributions and fourteen (56%) of these are between vertical joint distributions only.

For *Coordinate 6*, 83% of the possible combinations are significantly different, a total of 15 significant relations. Both secondary joint spacing distributions are significantly different for groups 1 and 3; for groups 3 and 4, only secondary vertical joint spacing distributions are significantly different. All distributions are significantly different for groups 1 and 2, 2 and 3, and 2 and 4. Nine of the fifteen significant relations (60%) are between secondary joint spacing distributions; the same number are also significantly different between vertical joint spacing distributions.

Summary. Forty-five of the significant relations (42.1%) are between horizontal joint spacing distributions, of which 30 are between secondary joint spacing distributions. The remaining 62 significantly different relations (57.9%) are between vertical joint spacing distributions. Thirty-nine (62.9%) are for secondary joint spacing distributions.

These results suggest that, although joint spacing is useful in distinguishing between the groups of tors along each coordinate, and is probably the single most important variable in doing so, it is not the only variable important in this respect. However, the importance of secondary joints, both vertical and horizontal, over primary joints with respect to characterizing the tors is indicated, as is the importance of vertical joints over horizontal joints.

Classification

There are significant differences in joint spacing between 6 of the 10 possible combinations of the 5 clusters. There are also 11 significant relations among the clusters, which comprise 27.5% of all possible comparisons between cluster/joint type combinations. The significant relations are shown in Table 7.

Table 7. Significant Differences between Clusters

Clusters	Significantly Different Variables
1 and 3	Secondary vertical joint spacing Primary horizontal joint spacing Secondary horizontal joint spacing
1 and 5	Primary vertical joint spacing Secondary vertical joint spacing
2 and 3	Primary horizontal joint spacing Secondary horizontal joint spacing
2 and 4	Primary vertical joint spacing
3 and 4	Secondary horizontal joint spacing
3 and 5	Secondary vertical joint spacing Secondary horizontal joint spacing

Seven significant relations (64%) are between secondary joint spacing distributions, which suggests secondary joints are more useful for characterizing these tors than primary joints. The number of significantly different distributions is about equal for the two joint types, suggesting vertical and horizontal joints are of equal importance.

The importance of other variables in each cluster, in addition to joint type, was evaluated by comparing the descriptors for each member of a significantly different pair. Variables common to both members of the pair, but of different "quality," may well be the basis for the significant differences between the clusters. For example, number of megacrysts helps define clusters 1 and 3, which are significantly different from each other with respect to joint spacing frequency. The rocks of cluster 1, however, contain medium to large numbers of megacrysts, whereas cluster 3 rocks contain none. Number of megacrysts is thus very important in differentiating between these two clusters. The common variables for each pair of significantly different clusters are shown in Table 8. Clusters 1, 2, 4, and 5 are each significantly different from two other clusters; Cluster 3 is significantly different from all others.

Table 8. Common Variables Between Cluster

Cluster	Variables	Cluster	Variables
1	Medium to large numbers of megacrysts	3	No megacrysts
	Medium- to coarse-grained feldspar		Fine-grained feldspar
	No schorl		Schorl
	Low to intermediate quartz abundance		Abundant quartz
	Tourmaline veins		No tourmaline veins
1	Medium to large numbers of megacrysts	5	Few megacrysts
	Medium- to coarse-grained potassium feldspar		Fine- to medium-grained potassium feldspar
2	Wide vertical joint spacing	3	Narrow vertical joint spacing
	Low to intermediate quartz abundance		Abundant quartz
2	Fine- to medium-grained feldspar	4	Medium- to coarse-grained feldspar
	Low to intermediate plagioclase abundance		Medium to high plagioclase abundance
	Low secondary joint spacing ratio		Intermediate secondary joint spacing ratio
	Wide secondary joint spacing		Intermediate secondary joint spacing
3	Fine-grained feldspar	4	Medium- to coarse-grained feldspar
	Abundant quartz		Low quartz abundance
	No megacrysts		Intermediate to abundant megacrysts
	Narrow vertical joint spacing		Intermediate vertical joint spacing
3	Narrow vertical joint spacing	5	Intermediate vertical joint spacing
	No tourmaline veins		Tourmaline veins
	No megacrysts		Few megacrysts

Summary. Four pairs contrast differences in joint spacing and, because of the duplication noted above, these differences may not in fact be real. On the other hand, they may be very real and the "doubling" of variables reinforces the true relations; there are joint spacing variables of importance to each cluster, but in only selected pairings do differences between them become significant. Regardless, number of megacrysts, feldspar grain size and joint spacing, excluding primary horizontal joint spacing, appear to be the most important variables with respect to differences between clusters. Quartz abundance and the presence or absence of tourmaline veins and schorl are only slightly less important in this respect.

Definitions of Landform Groups

The individual groups of tors identified as distinct from each other with their descriptors are as follows. *Group 1* consists of Bell Tor, the coarse-grained parts of West Mill Tor and Haytor Rocks, Roos Tor, Little Trowlesworthy Tor, the western block of Great Mis Tor, Mel Tor and both outcrops on Great Staple Tor. These tors occur mainly south of a line connecting Great Mis Tor and Bell Tor and many of them contain avenues (e.g. Haytor Rocks, Great Staple Tor). They have intermediate to large numbers of megacrysts, medium- to coarse-grained feldspar, narrow to intermediate vertical joint spacing, medium to high secondary joint spacing ratios, tourmaline veins, generally no schorl, small to intermediate amounts of quartz and form summit and spur tors (mainly summit).

Group 2 consists of Little Tor, the small tor southeast of Hound Tor, Heltor, Blackingstone Rock, Elsford Rock, Emsworthy Rocks, Scorhill Tor, Hookney Tor, Bellever Tor, Branscombe's Loaf, Lower Dunna Goat, Higher White Tor, Hart Tor, Great Links Tor, Brat Tor, Watern Tor and Black Tor. These tors occur throughout the moor, except in the west, and many of them are lamellar (e.g. Great Links Tor, Branscombe's Loaf). They have fine- to medium-grained feldspar, widely spaced vertical joints, low secondary joint spacing ratios, no tourmaline veins, and low to intermediate quartz abundances.

Group 3 consists of the two fine-grained exposures on West Mill Tor and at Haytor Rocks. These tors have fine-grained plagioclase and narrow vertical joint spacing. The rock is equigranular in texture. They are classified as summit tors, but it would be more correct to say that they are parts of summit tors: both exposures occur low on the outcrop faces and extend to ground level. They may in fact be sills. This may explain why this group has no spatial pattern.

Group 4 consists of Honeybag Tor, the northern and southern blocks of Hound Tor, Hayne Rocks, Down Tor, both sample sites on Oke Tor and the northern and southern blocks of Pil Tor. Most of these tors occur in the east, with the exception of Oke Tor in the extreme north and Down Tor in the south. They have intermediate to large numbers of megacrysts, medium- to coarse-grained feldspar, intermediate vertical joint spacing, no tourmaline veins, schorl, low quartz abundances, intermediate to abundant plagioclase, and form summit tors.

Group 5 consists of Yes Tor, South Hessary Tor, Combestone Tor, Belstone Ridge Tor, Middle Staple Tor, Littaford Tors, Hen Tor, Longaford Tor, Pew Tor, Wild Tor, the main part of Great Mis Tor, Ger Tor, King's Tor, Rippon Tor, Buckland Beacon, Sharp Tor and Doe Tor, and both outcrops on Sheeps Tor and on the Beardown Tors. These tors occur throughout the moor except in the northeast, often near the granite boundary (e.g. Middle Staple Tor, Buckland Beacon). Many of the altered or reddened tors (e.g. Hen Tor, Doe Tor) are included. They are feebly megacrystic, have fine- to medium-grained feldspar, narrow to intermediate vertical joint spacing, medium to high secondary joint spacing ratios, tourmaline veins, small to intermediate amounts of plagioclase and form summit and valleyside tors.

Summary

The five groups of tors were defined employing the combined procedures of principal coordinates analysis and non-hierarchical classification using 21 variables. The descriptors identified using these procedures were usually correct when compared to the data: the most common exceptions are plagioclase abundance and schorl. The tor groups exhibit different spatial patterns. In addition, joint spacing frequency was effectively used to identify statistically significant differences between the five clusters: four clusters are significantly different from two others, and one cluster, from all others.

Statistical comparison of joint spacing distributions for the tor groups indicates that secondary joint spacing is more important than primary joint spacing, regardless of joint type, and vertical joints are more important than horizontal joints. Other important variables distinguishing the groups in addition to joint spacing, excluding primary horizontal joint spacing, are number of megacrysts, feldspar grain size, quartz abundance, and the presence or absence of schorl and tourmaline veins.

CONCLUSIONS

As stated initially, the purposes of this study were two-fold: (1) to group or classify the Dartmoor tors by landform type using geomorphic, petrographic and structural factors, and (2) to determine which geologic factors are most important with respect to the development of granite landforms.

The analysis of correlations enabled successful grouping of tors by landform type because the procedure evaluates factors in pairs. Both summit and spur tors were characterized using statistically significant correlations as well as indirect or "third-party" relations. It is unfortunate that the coding system used for the nominal landform variables allowed no characterization of valleyside tors; all characteristics of valleyside tors as defined by analysis of correlations are intermediate between the characteristics of spur and summit tors because valleyside tors were coded "2." This may in fact be the case, but there is no way to determine this using the correlations.

Analysis of the correlation bonds suggests that the most important variables are the landform, composition and structural variables. The absence of significant correlations between the grain size and landform variables or between the joint spacing and rock texture variables suggests that neither grain size nor rock texture, which is related to grain size, are as important as the landform, composition and structural variables. The absence of a relationship, however, may result from the limitations of analysis of correlations in examining multiple relations. The results described in **Analysis of Correlations** clearly indicate that multiple relations exist between variables and a procedure such as analysis of correlations only addresses relations two-by-two.

Five groups of tors were defined using the combined multivariate procedures of principal coordinates analysis and non-hierarchical classification using 21 variables. Although landform was included as a defining variable in four of the five clusters, it was not possible to classify the Dartmoor tors by landform type using the multivariate procedures because so many other factors are important in distinguishing the tor groups. Summit tors occur in all four of these clusters; spur tors, in Cluster 1; and valleyside tors, in Cluster 5. Joint spacing frequency distributions were used effectively to identify statistically significant differences between the five clusters.

The fact that five tor groups rather than three (corresponding to the three landform types) were identified strongly suggests that other factors are at least as important as landform type in separating the 58 Dartmoor tors into groups. The variables that define the six important principal coordinates provide further information about the relative importance of the variables. The important variables, in coordinate order, are vertical joint spacing, the secondary joint spacing ratio, the presence or absence of tourmaline veins, number of megacrysts, plagioclase grain size, quartz and plagioclase abundances, landform, the presence or absence of schorl, and potassium feldspar grain size. Statistical comparison of the joint spacing distributions for the five clusters indicates that the most important variable categories distinguishing the five groups are rock texture, grain size, composition and structure. The geomorphic variables do not appear to be important. With respect to the structural variables, secondary joint spacing is more important than primary joint spacing, regardless of joint type, and vertical joints are more important than horizontal joints.

The geomorphic variables -- relative relief, landform and joint control of landform shape -- thus appear to be the least important of those evaluated. The geologic factors evaluated -- composition, rock grain size, rock texture and joint spacing -- are much more significant with respect to classifying and differentiating the Dartmoor tors than the geomorphic factors.

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